APPLICATION OF DIRECT TENSION TESTING TO LABORATORY SAMPLES TO INVESTIGATE THE EFFECTS OF HOT MIX ASPHALT AGING

A Thesis

by

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ABSTRACT

While the oxidation of binders in hot mix asphalt (HMA) pavements and its subsequent detrimental effects on pavement life have been well recognized in the last few years, many important issues have not yet been investigated. Understanding how best to design mixtures taking this phenomenon into account and achieving maximum durability is an important and complex issue. This study was aimed at characterizing the effects of oxidative aging on durability in terms of mixture fatigue resistance of laboratory mixed-laboratory compacted (LMLC) samples. Direct tension tests were conducted on HMA samples to measure mixture stiffness and a Modified Calibrated Mechanistic with Surface Energy (CMSE*) analysis method was used to predict fatigue life. The effect of various mix design parameters was evaluated to understand their importance with respect to the aging phenomena and mixture fatigue resistance.

Analysis of the results showed that aging has a significant negative effect on mixture fatigue resistance. Considerable increase in the stiffness modulus (E_{ve}) of the mixtures was observed with age for all three mixtures analyzed. Air voids (AV) played a substantial role in affecting the fatigue resistance with aging, but a difference of 0.5% in binder content near the optimum level did not statistically change mixture durability in terms of fatigue resistance with aging.

For the three mixtures in Texas included in this study, when comparing E_{ve}, one month of artificial aging in the laboratory was equivalent to 10.5 months of natural aging in the field. A good correlation was also found between the E_{ve} of the mixture and the Carbonyl Area (CA) and Dynamic Shear Rheometer (DSR) function of the extracted binder. Thus, a connection exists between the properties of the extracted binder, laboratory mixtures and field mixtures. This relationship will facilitate development of a more mechanistic aging component in pavement performance prediction models.

DEDICATION

To my parents, who taught me to believe in myself.

To Mona and Pooja, the two most wonderful sisters one can ask for.

To Marc, for all the love and happiness he brings into my life.

ACKNOWLEDGEMENTS

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CHAPTER I

INTRODUCTION

BACKGROUND

Hot Mix Asphalt (HMA) is a composite viscoelastic material consisting of approximately 95% aggregate by weight mixed with binder and compacted, whose behavior varies depending on the type of loading and temperature conditions. According to the National Asphalt Pavement Association (NAPA), 94% of the more than 2.5 million miles of paved roads in the United States utilize hot mix asphalt (0). In spite of this widespread usage of HMA pavements, engineers face many obstacles in building pavements with long service lives. Typical problems in asphalt pavements include rutting, thermal cracking and fatigue cracking. With the increasing costs of petroleum affecting the cost of materials in asphalt pavements and the high costs associated with transporting quality aggregates, it is vital that the transportation system be constructed and maintained in such a way as to maximize the benefits associated with these costs. Hence, it is of primary importance to focus research on understanding the various factors which contribute to the reduction of pavement service lives.

Fatigue failure in HMA pavements occurs due to repeated load applications over a prolonged period of time. Complicating this concept of fatigue damage is the oxidative aging of binder in the pavement with time (2). Previous studies indicate that this oxidation increases the binder stiffness and reduces healing and stress relaxation of the binder. These property changes make it more susceptible to fatigue failure, thus reducing the pavement service life. Although the effect of aging on binder has been studied to some degree, many important issues have not yet been investigated to better understand the phenomenon and provide tools for quantifying the effect of aging in mix design and analysis. One such issue would be studying the impacts of oxidative aging on the durability of HMA mixtures in terms of mixture fatigue resistance. Incorporating aging in HMA mix design and analysis would better represent field conditions and properties and subsequent performance, but depending on the interconnected air voids (AV) or porosity of the mixture and other mixture parameters and material properties, the interaction between the aggregate and the binder differs from mixture to mixture. Thus, understanding how best to design mixtures to take the phenomenon of oxidative aging into account and achieve maximum durability is an important and complex issue.

Various methods have been used to characterize fatigue failure in HMA pavements. One of the recently developed methods that has proved to be promising in terms of capturing aging effects in HMA mixtures is the Modified Calibrated Mechanistic with Surface Energy (CMSE*) approach. The CMSE* method uses fundamental material properties including surface energies associated with binders and aggregates, Paris' Law fracture parameters, and calculates shift factors which incorporate the effects of mixture anisotropy, healing, and simplified aging using a multiplicative factor based on changes in binder properties (3, 4). While this effort to include aging as a shift factor is a step in the right direction, it is still empirical in nature. Understanding the contribution of aging in the deterioration of HMA is critical in development of a more mechanistic design method.

To understand the impact of oxidation on long-term pavement performance, a brief introduction of related concepts and issues is presented. Binder oxidation chemistry suggests that carbonyl compounds form as a result of oxidation, and the exact nature and rate of formation of the compounds depends on the temperature, partial pressure and varies from asphalt to asphalt (5, 6, 6). This oxidation of the binder results in its hardening which in turn leads to an increase in stiffness of the mixture. This stiffening of the mixture in pavements causes early fatigue failure. While the mechanism of the fatigue life decline with oxidation is not yet well understood, related studies indicate that it is an important phenomenon and that there can be significant differences between different mixture designs. Understanding these differences is an important issue investigated in this study. Once these differences are well understood, various mix design parameters (AV, binder content, binder composition, aggregate type, and aggregate gradation) may be able to be controlled to improve mixture fatigue resistance.

PROBLEM STATEMENT

HMA mixtures experience a variety of distresses as a part of their service life. Minimizing these distresses to improve and maintain the pavement condition can help save millions of dollars per year. The type of distress investigated in this study is the loss of fatigue resistance due to oxidative aging of the binder. The study aims at characterizing the effects of aging in laboratory-mixed laboratory compacted (LMLC) samples. Direct tension tests were conducted on HMA samples to measure mixture stiffness and a Modified Calibrated Mechanistic with Surface Energy (CMSE*) analysis method was used to predict fatigue life. The effect of the various mix design parameters (AV, binder content, aggregate type, type of mix, etc.) was evaluated to understand the importance of each factor with respect to the aging phenomena. The research conducted for this thesis was performed as part of Texas Department of Transportation (TxDOT) Project 0- 6009- Evaluation of Binder aging and its influence in aging of hot mix asphalt concrete. Other parts of this project included studying the effects of oxidative aging on field cores and extracted binder. The LMLC mixture results from this study were correlated with binder properties to better understand how oxidation in binders translates to changes in mixture properties. The LMLC results in this study were also compared to the field results in an effort to establish a meaningful relationship between laboratory and field behavior with respect to aging.

RESEARCH OBJECTIVES

The primary objectives of this study are:

1. To investigate the effects of aging on the fatigue resistance of three selected HMA mixtures: Laredo, Childress and Paris (named after actual field pavements constructed in TxDOT districts)
2. To evaluate the importance of each of mix design parameter (including AV, binder content and type of mix) with respect to the loss of mixture fatigue resistance due to oxidative aging
3. To compare the laboratory results with the corresponding field results and develop a relationship between the artificially aged LMLC samples and naturally aged field samples
4. To correlate the binder and mixture data to establish a meaningful relationship between mixture and binder properties

WORK PLAN AND SCOPE OF STUDY

The types of mixtures tested and analyzed were chosen based on consideration of the following four factors and selection of representative materials and field conditions: the number of sites, levels of aging, AV, and binder content.

Three mixtures from three different sites in Texas (Laredo, Childress and Paris) were tested as a part of the study. Prior to laboratory testing, the samples were subjected to artificial laboratory aging for periods of 6, 9, and 12 months at a constant temperature of

60°C in an environmental room. A D-optimal statistical design was developed using four levels of aging, three levels of AV and three levels of binder content.

Direct tension tests developed at Texas A&M named the Viscoelastic Characterization test (VEC) and Repeated Direct Tension (RDT*) tests were used to test the samples. The general framework of the CMSE* fatigue analysis approach was utilized based on its ability to capture the effects of aging on HMA mixture fatigue resistance. This approach utilizes fundamental material properties such as asphalt mixture relaxation modulus in tension and compression, dissipated pseudo strain energy and surface energies for both binders and aggregates to characterize HMA mixture fatigue resistance. This particular method of analysis was selected as it uses fundamental material properties, accounts for realistic mixture behavior, produces fatigue life predictions with low statistical variability, and exhibits a good potential to quantitatively incorporate aging effects in HMA mix design in terms of fatigue resistance (8, 9, 10).

The scope of this study is limited to:

- Three different mixtures from three different sites in Texas: Laredo (LRD), Childress (CHS) and Paris (PAR)
- Four different aging levels: 0 months, 6 months, 9 months and 12 months in the artificial aging room at 60˚C
- Three different AV levels: Low (<4%), Medium (4-7%) and High (7-9%)

- Three binder contents: Optimum-0.5%, Optimum and Optimum+0.5% where the optimum level was defined for each mixture based on volumetric design by TxDOT specifications (11)

DESCRIPTION OF CONTENTS

The thesis is divided into five chapters. Chapter I gives an introduction about the topic describing the background, problem statement, work plan and the scope of study. Chapter II describes the literature review in detail. Chapter III deals with the details of the experimental design and methodology, materials and the testing methods used. Chapter IV discusses the results and the analysis of the data while Chapter V provides the conclusions and recommendations for future research.

CHAPTER II

LITERATURE REVIEW

A review of the literature available on testing of fatigue resistance of HMA, binder aging and its effects on fatigue resistance of HMA was done as a part of this study; and a summary is presented in this chapter.

DEVELOPMENT OF THE SELECTED FATIGUE ANALYSIS METHOD

Many different testing methods have been developed to effectively characterize the fatigue properties in HMA mixtures. These approaches range from empirical methods to mechanistic-empirical methods to purely mechanistic methods (12). The tests can be generally classified as simple flexure, indirect tension and direct tension tests. Each of these tests has its own set of advantages and disadvantages, and researchers have been constantly making efforts to improve the test methods to suit different material and testing needs. Data from these fatigue tests is usually used to predict the number of load cycles to failure (N_f) which acts as a reasonable surrogate of the pavement service life.

A testing and analysis method using direct tension testing methods to determine the fatigue characteristics of asphalt called the Calibrated Mechanistic with Surface Energy (CMSE) approach has been developed recently at Texas A&M University (8). The CSME approach is based on the theory that HMA is a composite material which is viscoelastic in nature and that it heals and cracks. When characterizing the fatigue damage in mixtures, two separate phenomena are considered, the resistance to crack and the ability to heal. The CMSE approach captures these effects in a somewhat complicated and time-consuming analysis method. The tests required in the CMSE analysis are Tensile Strength (TS), Relaxation Modulus (RM) and Repeated Direct Tension (RDT) tests. This method of analysis has been compared to more conventional methods like the Mechanistic Empirical (ME) method, the Mechanistic-Empirical Pavement Design Guide (MEPDG) method, and the Calibrated Mechanistic (CM) method by Walubita (8). According to this study, even though the CMSE analysis was more time consuming, the tests were relatively short and easy to perform and the results were less variable. The tests required for this analysis are shown in a graphical form in Figure 1.

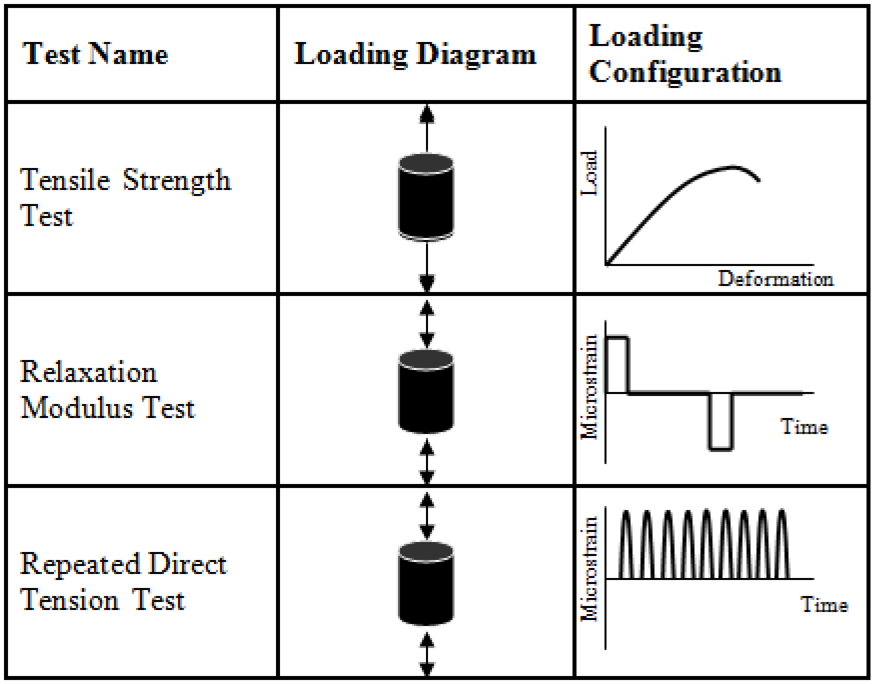


Figure 1: Fatigue tests used in CMSE analysis. Adapted from Walubita (8)

The CMSE method takes into account several shift factors that include anisotropy, healing, and aging. It includes fracture mechanics to describe the process of crack initiation and crack propagation in HMA. Studies at Texas A&M University have indicated that while the TS test was a good test, it was difficult to control the deformation in the samples so as to not cause damage. In addition, the RDT included unwanted healing of the sample due to long rest periods during testing. It was also observed that the CMSE method was time-consuming with respect to data collection and analysis. These disadvantages have encouraged researchers to improve the testing methods to help collect better data in less time (10).

Efforts to overcome these issues have led to the development of two new testing methods called the Viscoelastic Characterization (VEC) test and the Modified Repeated Direct Tension (RDT*) test. The VEC test is used as a replacement to the RM test. It calculates the Relaxation Modulus and the rate of relaxation using the strains and displacements determined from the test. The RDT test has been modified to include compressive stresses in the testing method, and the haversine loading has been slighted revised to reduce the rest periods. The data from the VEC and RDT* is used to calculate the Paris law coefficients and then the Dissipated Pseudo Strain Energy (DPSE) which is then used to calculate the number of load cycles to crack initiation (N_i) and number of load cycles to crack propagation (N_p). The calculated N_i and N_p are then used to find the number of load cycles to failure (N_f).

With the development of macros to help analyze the data from the VEC and RDT* tests, the data analysis takes less time and aids in the testing and analysis of many more samples than previously possible (10). Following these improvements, the CMSE* method is considered to be an efficient fatigue testing method to characterize aging in samples. A Summary of input and output variables in the CMSE* analysis adapted from Walubita (13) is included in the Appendix.

AGING IN MIXTURES

Studies have indicated that binder oxidation changes physical and chemical properties of binders and makes binders harder and more susceptible to brittle failure. To understand the phenomenon of aging, the basics of the oxidation reaction are presented briefly. Studies by Petersen (6), observed that carbonyl compounds are formed with exposure to oxygen. The exact nature and amount of these compounds depends on the type of binder and the environmental conditions. But, it has been generally accepted that carbonyl compounds can be used as a reasonable substitute for oxidative changes. Hence, one of the accepted methods of characterizing aging in binders is to determine the carbonyl area formed with time.

Exposing the binder to oxygen creates carbonyl compounds, primarily by oxidizing aromatic compounds in the naphthene aromatic, polar aromatic and asphaltene fractions. These more polar compounds result in stronger associations, leading to higher viscosity and stiffness in the binder (14). This explains why binders become stiffer and more brittle with time. Another function commonly used to characterize aging in binders is the Dynamic Shear Rheometer (DSR) function which provides a good relationship with binder ductility and correlates with long term pavement durability. This parameter for a number of asphalts has been reported by Glover (15).

The process of calculating the CA and the DSR function is described briefly. The sample cores are broken into small pieces, and solvents are used to extract the binder from the aggregate. The solvent is then carefully separated from the binder to extract just the binder from the mixture. The DSR testing method according to AASHTO T 315 is run on the extracted binder to determine the DSR function, and a FTIR spectrometer is used to determine the CA.

CA and DSR functions were used as a measure of aging in extracted binders in this study. Comparisons of mixture parameters and binder properties including CA and DSR were compared in an effort to correlate the mixture and binder data.

INFLUENCE OF AGING ON FATIGUE RESISTANCE OF MIXTURES

While it has been well recognized that the binder oxidizes as it ages in HMA pavements and thus affects its durability, the subsequent change in fundamental properties of mixtures which affect HMA mixture fatigue resistance are not well understood. The questions arising in this context are: a. How does the change in binder properties affect the overall pavement service life? b. How much of an effect do the various mix design parameters have on this phenomenon? Recent studies in this area have suggested that aging has a very significant negative impact on pavement fatigue life (4,16, 17, 18).

Jung (16), conducted a study on binder oxidation in 15 different Texas highway pavements to compare the impact of binder oxidation on HMA mixture aging and HMA mixture fatigue resistance. It was observed that the binders in the pavements became stiffer and more brittle even 6 inches below the surface. Binder oxidation significantly affected the decline of strain-controlled fatigue due to the detrimental impact of the binder durability on the mixture. Also, the HMA mixture fatigue performance was found to be a function of the mix design. According to the results obtained, mixtures stiffened significantly in response to binder oxidative aging. This stiffening was reflected in both the tensile relaxation modulus of the mixture and the dynamic shear moduli of the binder. However, it was suggested that more fundamental studies are required to understand how the decline of fatigue life is a function of mixture parameters.

A study was conducted by TxDOT where binder aging in the field was evaluated and the effect of accessible AV was studied in particular (5). In this work, two layers in each of three pavements in three TxDOT districts were evaluated. The measurements provided an indication of binder aging in pavements and suggested strongly that binders age even at significant depth into the pavement. Results showed that binder oxidation greatly affects mixture fatigue performance and mixture rheological properties. Lower accessible AV also correlated with a lower rate of binder oxidation and hardening.

Baek (18) studied the aging of HMA mixtures at four different laboratory simulated levels. At each level of aging, mechanical properties were determined via dynamic modulus testing, monotonic direct tension testing, and cyclic fatigue testing. The effects of aging on linear viscoelastic and damage properties were studied. It was observed that the stiffness of the mix increases with age .The fatigue failure was also found to be dependent on the temperature and aging level. However, it was concluded that the results were highly dependent on the materials used and environmental conditions. Further research was recommended to understand the exact nature of aging in the laboratory and its relation to the field.

A study conducted by Walubita (4) for TxDOT is the direct predecessor of this work. This study dealt with laboratory validation of the CMSE fatigue analysis method under controlled-strain conditions. The effect of aging on fatigue resistance of the mixtures was studied, and two different mixtures were studied to understand the effect of type of mix on the fatigue resistance. It was concluded in the due course of the study that the HMA mixture fatigue resistance was a complex function of:

- Mix design parameters (AV, Voids in Mineral aggregate (VMA), binder content);
- Material properties (binder, aggregate and HMA); and
- Traffic, Pavement structure and Environment.

Analysis of the results showed that CMSE analysis provides a promising methodology to characterize fatigue in HMA. Also, for the conditions and materials studied in this experiment, aging proved to reduce the stiffness and healing of the binder. A mixture with as softer binder stiffened much faster than a mixture with stiffer binder. This showed that a mixture with a stiffer binder does not necessarily perform poorly in fatigue. Further research was suggested to study the effects of the mixture parameters on the fatigue performance individually.

It was concluded that the mixture parameters interact internally, complicating the effect of fatigue damage, and that they should be considered separately while modeling the mixture fatigue resistance. An increase in binder content showed an improvement in the fatigue resistance which was reflected in a corresponding increase in N_f. Also, for the same binder, the mixture with granite aggregates exhibited a significantly higher N_f in comparison to a mixture with limestone aggregate. Additional validation of the CMSE analysis method with additional HMA mixtures and laboratory aging exposure conditions was suggested.

The collected literature and related studies conclude that further research is required to characterize the effects of aging in mixtures. A summary of results from recent studies which are directly related to this study are as follows:

a. Fatigue life decreases significantly primarily as a result of aging due to binder oxidation and its subsequent effect on mixture properties.

b. The decrease in fatigue life is a function of more than just the binder stiffening due to oxidative aging. Thus, mixture parameters that may be controlled during the mix design process are important to ensure adequate fatigue resistance.
c. Studying different mixtures separately is essential as different mixtures show distinctive declines with aging
d. The CMSE* approach is an efficient method to characterize the different mixture responses to aging.

So, the decline of mixture fatigue resistance under controlled-strain conditions is an important phenomenon that varies from mixture to mixture. Unknown, however, are the quantitative contributions of each of the various mixture parameters (AV, binder content, binder composition, aggregate type, aggregate gradation) to the differences in decline of mixture fatigue life with binder oxidation; and quantitative assessment of these differences is essential.

CHAPTER III

EXPERIMENTAL METHODOLOGY AND TEST PROCEDURES

Samples from three different sites in Texas (LRD, CHS and PAR) were tested as a part of this study. The types of mixtures to be tested and analyzed were chosen taking the following four factors into consideration to integrate a wide spectrum of materials and field conditions: the number of sites, levels of aging, AV and binder content.

Prior to laboratory testing, the samples were subjected to artificial laboratory aging for periods of 6, 9, and 12 months at a constant temperature of 60°C in an environmental room. A statistical design was developed using four levels of aging, three levels of AV and three levels of binder content. This experiment aims at characterizing the effects of aging in HMA mixtures with different mixture parameters like AV, binder content and type of mixture. Fatigue characterization tests were run on these samples, and the test results were used to build meaningful relationships between the mixture parameters and HMA fatigue resistance.

The following sections give a detailed description regarding the individual material properties and the HMA mixture properties. A description of the D-Optimal design to consider the three parameters of interest (AV, binder content, level of aging) in a fractional factorial experiment, followed by the sample preparation and test protocols are included. Details about the artificial aging method and the test procedures are also presented.

MATERIAL SELECTION AND PREPARATION

The LMLC specimens were prepared based on the mix designs for the three different pavements in three TxDOT districts: LRD, CHS and PAR. The three mix designs correspond to US 277, US 83 and SH 24 highways, respectively. The virgin material at the time of construction of these highways was collected and used in the laboratory to make the LMLC samples. The field cores from these sites were collected as a part of the same TxDOT project to develop relationships between the laboratory aged and field aged samples.

Figure 2 shows the different environmental zones in Texas. It can be observed that the three selected sites belong to three different zones: Laredo to the Dry-Warm, Childress to Dry-Cold and Paris to Wet-Cold. This was done in an effort to capture the effects of the environmental zones on aging.

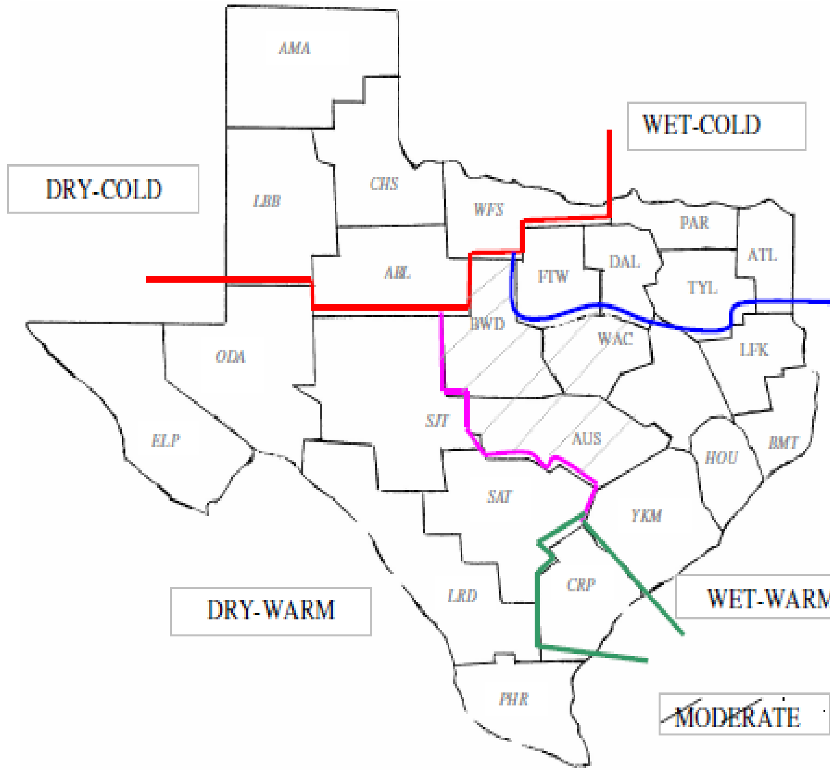


Figure 2: Texas Environmental Zones

The following sections provide details regarding the individual material properties and the asphalt mix properties.

LAREDO (LRD)

The LRD samples were prepared based on a TxDOT Type C mix previously used in the Laredo District for US Route 277. A TxDOT Type C mix is a dense graded HMA mix which is used as a coarse surface mix (11). The aggregate gradation of the LRD mixture is shown in Figure 3. The detailed mix design is included in the Appendix.

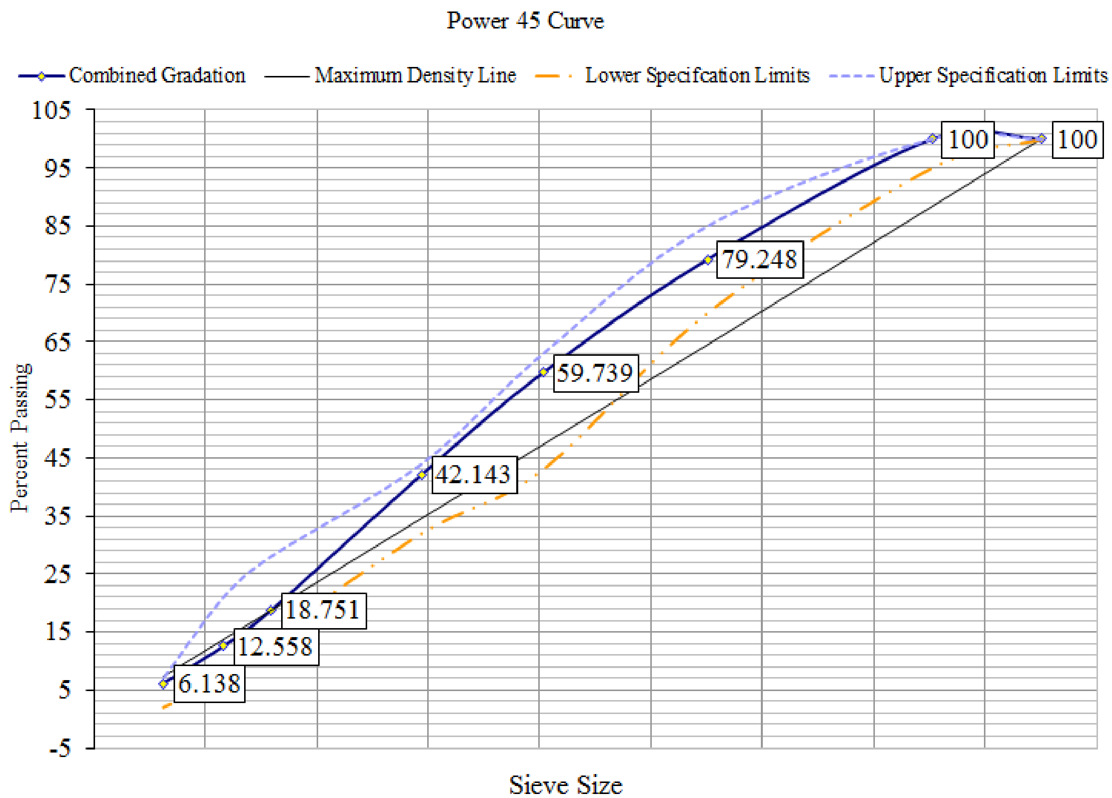


Figure 3: Aggregate gradation of Laredo

The aggregates used in this mixture are a blend of four different aggregate gradations with the addition of 0.5% of a liquid antistripping agent. Three of the aggregates consist of limestone including coarse limestone aggregate, a blend of TxDOT Type D and Type F limestone aggregates, and manufactured sand. Samples of these aggregates were blended, and a wet sieve analysis was performed. The final gradation was adjusted to account for any extra fines discovered during the wet sieve analysis.

The binder graded as PG 70-22 from Valero was used to make the samples as it was the same binder used during the construction of US 277. An optimum asphalt content equal to 4.5% was used.

CHILDRESS (CHS)

The CHS samples were made according to a TxDOT Type D mix used in the Childress District for US Route 83. A TxDOT Type D mix is a dense graded HMA mix and is used as a fine surface mix (11). Figure 4 shows the aggregate gradation of the mixture used.

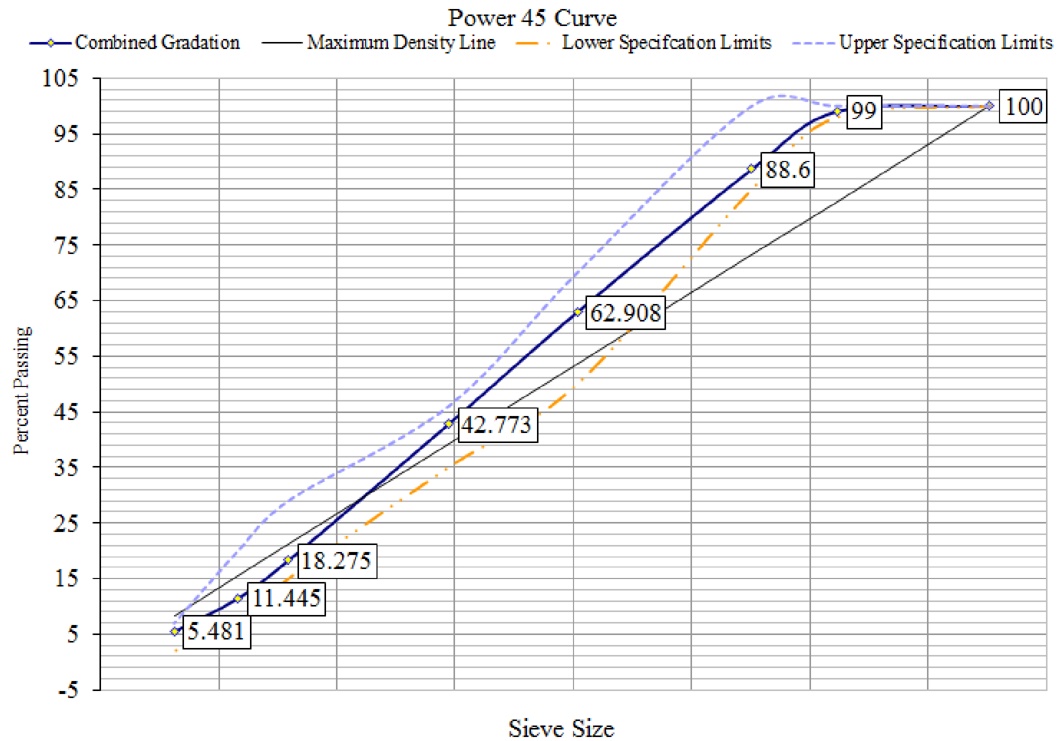


Figure 4: Aggregate gradation of Childress

This mix design combined three different aggregate gradations with the addition of 2% lime as an antistripping agent. Three of the aggregates consist of granite including coarse granite aggregate and crushed screenings. These aggregates were blended, and a wet sieve analysis was performed. Binder graded as SemMaterials PG 70-28 was selected based on the binder type used for US Route 83. An optimum asphalt content equal to 5.3% was used. Detailed aggregate gradations and the mix design are included in the Appendix.

PARIS (PAR)

The PAR samples were based on a TxDOT Type D mix used in the Paris District (US State Highway 24) (11). Aggregates selected for this mixture consist of three different aggregates including D rock, screenings and river sand with the addition of 1% of a liquid antistripping agent. LION PG 64-22 binder was selected with an optimum asphalt content equal to 5.4%. Figure 5 shows the aggregate gradation of the mixture used. Detailed aggregate gradations are included in the Appendix.

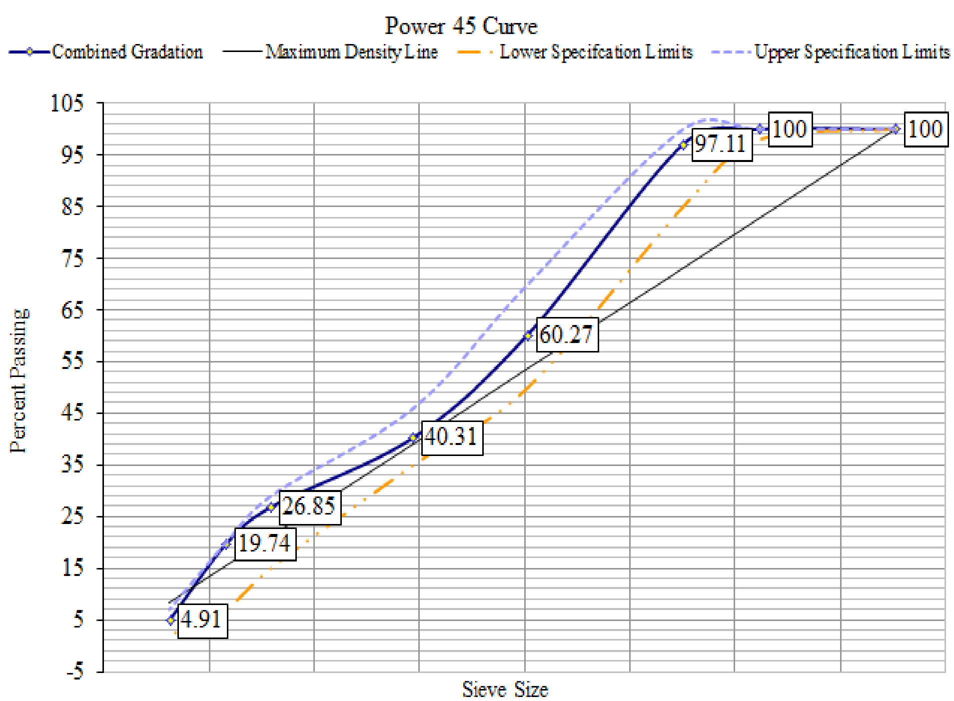


Figure 5: Aggregate gradation of Paris

Table 1 : Summary of the three mixtures

FACTOR	LEVELS		
	LAREDO	CHILDRESS	PARIS
Binder Type	PG 70-22	PG 70-28	PG 64-22
Aggregate Type	Limestone	Granite	Sandstone
Mix Type	• TxDOT Type C • Dense graded • Coarse Surface	• TxDOT Type D • Dense graded • Fine Surface	• TxDOT Type D • Dense graded • Fine Surface
Texas Environmental Zone	Dry-Warm	Dry-Cold	Wet-Cold
Aging Levels	0,6,9 and 12 months at 60˚C		
Binder Contents	Optimum -0.5%, Optimum and Optimum +0.5%		
Air Voids	Low (<4%), Medium (4-7%) and High (>7%)		

Table 1 shows a summary of the three mixtures and the proposed mix design parameters and levels considered in the laboratory experiment design for the aging experiment in this study.

STATISTICAL EXPERIMENTAL DESIGN

One of the preliminary tasks in this study was to develop a statistical experimental design which considers all the necessary factors within the scope and budget of the study. A D-optimal design was developed to incorporate the effect of several factors and their interactions on the fatigue resistance of HMA. Statistically, a D-optimal design is a computer generated statistical design that allows parameters to be estimated without bias and with minimum variance. The three factors considered in this experiment are aging level, binder content, and AV. The design aims at minimizing testing, but still has the ability to estimate the main effects of the factors and the two way interactions between them.

The four aging levels considered were 0 months, 6 months, 9 months and 12 months. The three levels of binder contents were Optimum -0.5%, Optimum and Optimum +0.5%. The optimum level of binder content varied depending on the mixture selected. The three levels of AV were: Low (<4%), Medium (4-7%) and High (7-9%). With the given number of factors considered, the D-optimal design generated consisted of 27 combinations. Each run represented four LMLC specimens for use with two replicates for testing and two as reserve. This D-optimal design not only provided high precision estimates of all main effects and two-way interactions with a minimum variance, but also reduced the number of factor-level combinations from 36 to 27. The detailed D-optimal design is shown in Table 2.

Table 2: D-optimal design

RUN	AGING (months)	BINDER CONTENT	AIR VOIDS
1	0	Opt-5%	Low
2	0	Opt-5%	High
3	0	Opt+5%	Medium
4	0	Opt+5%	High
5	0	Opt+5%	Low
6	0	Optimum	Medium
7	0	Optimum	High
8	6	Opt-5%	High
9	6	Opt-5%	Medium
10	6	Opt+5%	Low
11	6	Opt+5%	Medium
12	6	Optimum	High
13	6	Optimum	Low
14	6	Optimum	Medium
15	9	Opt-5%	High
16	9	Opt-5%	Medium

Table 2, Continued.

RUN	AGING (months)	BINDER CONTENT	AIR VOIDS
17	9	Opt+5%	Medium
18	9	Opt+5%	Low
19	9	Opt+5%	High
20	9	Optimum	Medium
21	12	Opt-5%	Medium
22	12	Opt-5%	Low
23	12	Opt+5%	Low
24	12	Opt+5%	High
25	12	Optimum	Low
26	12	Optimum	High
27	12	Optimum	Medium

When implementing this design, the order of testing was randomized to reduce bias by equalizing the independent variables not considered in the design.

The air void and binder content ranges are shown in Table 3.

Table 3: Air void and binder content ranges for the three mixtures

BINDER CONTENT				AIR VOIDS	
	LAREDO	CHILDRESS	PARIS		
Optimum -0.5 %	4.0 %	4.8%	4.9%	Low	< 5%
Optimum	4.5 %	5.3%	5.4%	Medium	5% - 7%
Optimum +0.5 %	5.0 %	5.8%	5.9%	High	> 7%

SAMPLE PREPARATION

Based on the D-optimal design, different sets of mixtures were prepared for the three different sites: LRD, CHS and PAR. Each site had 27 samples with different combinations of AV and binder content. Four samples were prepared for each type of combination. Two of these samples were tested while two others were stored for future use.

The HMA samples were fabricated using the Super Gyratory Compactor (SGC). Descriptions of each of the mix designs are included in the Appendix. The aggregates used for the sample preparation were heated to a temperature of 149°C and left overnight to remove any moisture. The binder was also heated to the same temperature for 2 hours before mixing. The mixture was then short term oven aged at the molding temperature of 135°C for four hours as prescribed by AASHTO R30. This short term oven aging is intended to represent the aging that takes place during the mixing, transporting and placing of HMA in the field.

MOLDING OF SAMPLES

The samples were prepared using the SGC at the required AV content. The samples were molded and compacted into cylinders of 6 inch (height) by 6 inch (diameter). The initial air void content in these compacted samples was measured to be higher than the specified content due to the compaction conditions imposed by the SGC mold. To assure a more consistent AV distribution in the specimen, the samples were molded at a higher air void content and then cored to a 4 inch diameter. The sample then had 1 inch trimmed from each end to produce the final 4 inch diameter by 4 inch high sample with the correct low, medium or high range of AV. The coring and trimming of the LMLC samples provided samples with a more even distribution of AV, similar to what would be found in the field.

AGING OF THE SAMPLES

An approximate simulation of road-aging is achieved using an environmental room controlled to 60 °C and 1 atm air with 25 percent relative humidity. Heated air at 60°C circulates freely around specimens in an environmentally temperature controlled room and accelerates oxidation of the binder in the HMA mixtures (14). This aging was carried out for 6 months, 9 months and 12 months to create the four levels of aging specified in this study. The samples tested right after fabrication constitute the zero aging level and represent the state of the pavement at the time of paving.

GLUING THE SAMPLES

The sample was centered and glued to steel platens using a vertical gluing jig. Equal parts of the 2-ton epoxy hardener and resin were mixed together thoroughly, and this mix was used to glue the steel platens on either face of the sample. The freshly glued sample was then left in it for a minimum of four hours to ensure complete setting of the glue. Once the sample was taken out, vertical lines were drawn on the sample surface using a ruler at 120º from each other. Then, LVDT were glued at 1 inch from the top and the bottom edge of the sample. This placed six LVDTs all around each sample. The vertical gluing jig can be seen in Figure 6.

Figure 6: Vertical gluing jig

DESCRIPTION OF TESTS

The general framework of the CMSE fatigue analysis approach was used in testing the samples as demonstrated in TxDOT Project 0-4468 (4,13). This approach utilizes the fundamental material properties, accounts for realistic mixture behavior, produces fatigue life predictions with low statistical variability, and exhibits the greatest potential to quantitatively incorporate aging effects in HMA mix design in terms of fatigue resistance.

Two new tests were developed to replace the time consuming and highly variable tests used in the CMSE method called the Viscoelastic Characterization (VEC) test and the Modified Repeated Direct Tension (RDT*) test. These tests were used for the samples in this study as they have proved to show lower variability and better results in less time. A brief description of the two test procedures is described subsequently.

VISCOELASTIC CHARACTERIZATION (VEC) TEST

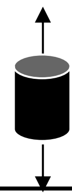
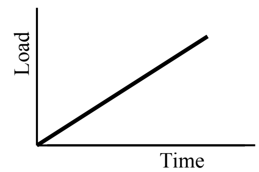
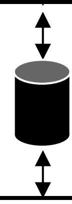
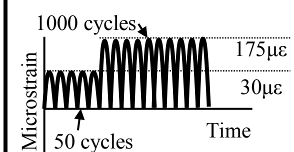
The VEC test was conducted at three different temperatures: 50°F (10°C), 68°F (20°C) and 80°F (30°C). The specimen was preconditioned at 50°F (10°C) for approximately 2 hours to ensure uniform temperature throughout the specimen. A linearly increasing tensile load at a rate of 50.8 μm per minute was used to assure sufficient data was obtained at all testing temperatures. The incremental monotonically increasing load was continued until the strain reached a maximum value of about 100 microstrain, and load readings were collected every 0.01 seconds. The sample was then reconditioned and retested at 68°F (20°C) and 80°F (30°C). The test ran for approximately 10-90 seconds depending on the testing temperature. The actual stress and strain values were then calculated by subtracting the initial loading, displacement and time data from each subsequent reading. These values were then used to develop the relaxation modulus and phase angle master curves. The experimental set up is shown in Figure 7.

Recorded load and displacement data from the LVDTs for each temperature were used to calculate stress and strain. These values were averaged and defined using a fitting curve at each temperature. Fitting parameters from these curves were then used, in conjunction with Laplace transformations and calculated shift factors, to determine the relaxation modulus (E_t) master curve and the complex modulus (E*) master curve at 20° C.

MODIFIED REPEATED DIRECT TENSION (RDT*) TEST

The RDT* test characterizes the fracture damage potential of asphalt mixtures through the rate of change of the accumulation of dissipated pseudo strain energy (DPSE). In this test method, the specimen was first preconditioned at 68°F (20°C). A haversine load with a maximum vertical strain of 30 microstrain for 50 cycles was applied at a frequency of 1 Hz to avoid damage to the specimen and facilitate calculation of the undamaged viscoelastic phase angle and relaxation modulus. Then, after a rest period of 10 minutes, another haversine load with a maximum strain of 175 microstrain for 1000 cycles was applied at the same frequency. During this loading period, no rest period was introduced. Though visible cracks may not be apparent, at the completion of the test the sample was damaged and cannot be retested. Table 4 shows the loading configuration of the two tests.

Table 4: Descriptions of tests used in CMSE* analysis

Test Name	Loading Diagram	Loading Configuration
Viscoelastic Characterization Test		
Modified Repeated Direct Tension Test		

Calculation of stress and strain in the RDT* test was the same as in the VEC test. The load readings were collected every 0.01 seconds. The initial time, load and displacement values were subtracted from each subsequent reading in order to determine the actual loads and displacements experienced by the sample.

The RDT* method, as developed by Luo et al. (19), separates the tension and compression components of the test and calculates their related material properties separately. Stiffness modulus (E_{ve}) was calculated from the undamaged part of the RDT* test. The strain and the stress values were then used to calculate the Dissipated Pseudo Strain Energy (DPSE) and the rate of fracture damage accumulation (b). This b value was then be used in the CMSE* equation to determine the loads to crack initiation value (N_i). With the data obtained from the VEC and RDT* tests and with the analysis completed in order to determine Elastic modulus from the relaxation modulus master-curve (E_t), the slope of the log relaxation modulus versus log time (m), DPSE (W_{R1}), and the rate of damage accumulation (b), calculations were then made to determine Paris' Law fracture coefficients A and n. The next step in the process was calculating the loads to crack propagation value (N_p) using the values A and n. Then summing the values of N_i and N_p, the number of loads to failure (N_f) were calculated.

To manage the complex calculations in this method, macros were developed which reduce the analysis time greatly (10). This also makes the analysis procedure comparatively error-free and more efficient. Detailed descriptions of the macros and their development procedures can be found in Lawrence's study (10).

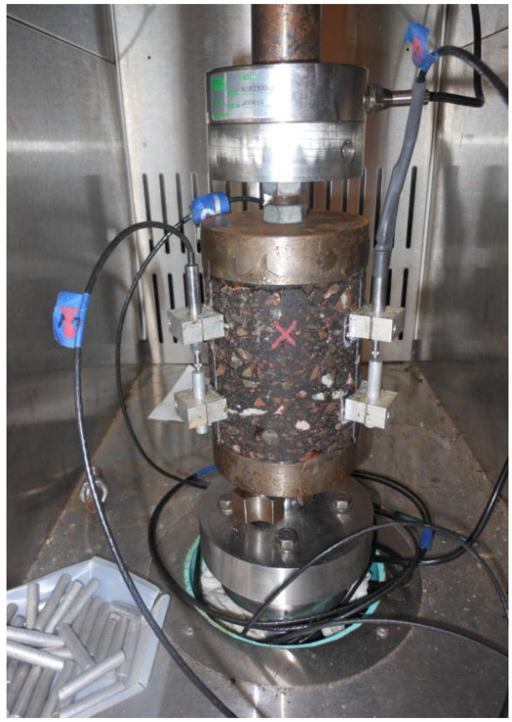


Figure 7: Test setup for LMLC samples

CHAPTER IV

RESULTS AND ANALYSIS

The results of the VEC and RDT* tests were carefully recorded and the CMSE* method of analysis was used to analyze the data collected. Each of the three sites had 27 specimens with two replicates for each mix type. The results were studied, and the effects of three factors (aging, AV and binder content) on the fatigue resistance are presented in detail in this chapter. The LMLC results have also been correlated to the field results to build meaningful relationships between the artificially aged samples and the field aged samples. Similarly, efforts have been made to understand the behavior of the asphalt mixture in comparison to the binder by correlating the binder and mixture results.

EFFECT OF MIXTURE PARAMETERS ON FATIGUE DAMAGE CHARACTERISTICS

EFFECT ON STIFFNESS MODULUS (E_{ve})

The stiffness modulus (E_{ve}) which is calculated from the undamaged part of the RDT* test was used to characterize the stiffness of mixtures in this study. Figure 8 shows the E_{ve} values for the three different sites at optimum binder content and the medium AV range. E_{ve} increased considerably with age confirming that the mixture becomes stiffer with time. Laredo was the stiffest of the three mixtures, while Childress was the softest. In addition, Laredo continued to show an increase in the modulus even after nine months of aging while the other two sites started to level off. This could indicate that stiffening due to oxidative aging is sensitive to the type of mixture and that each mixture behaves differently.

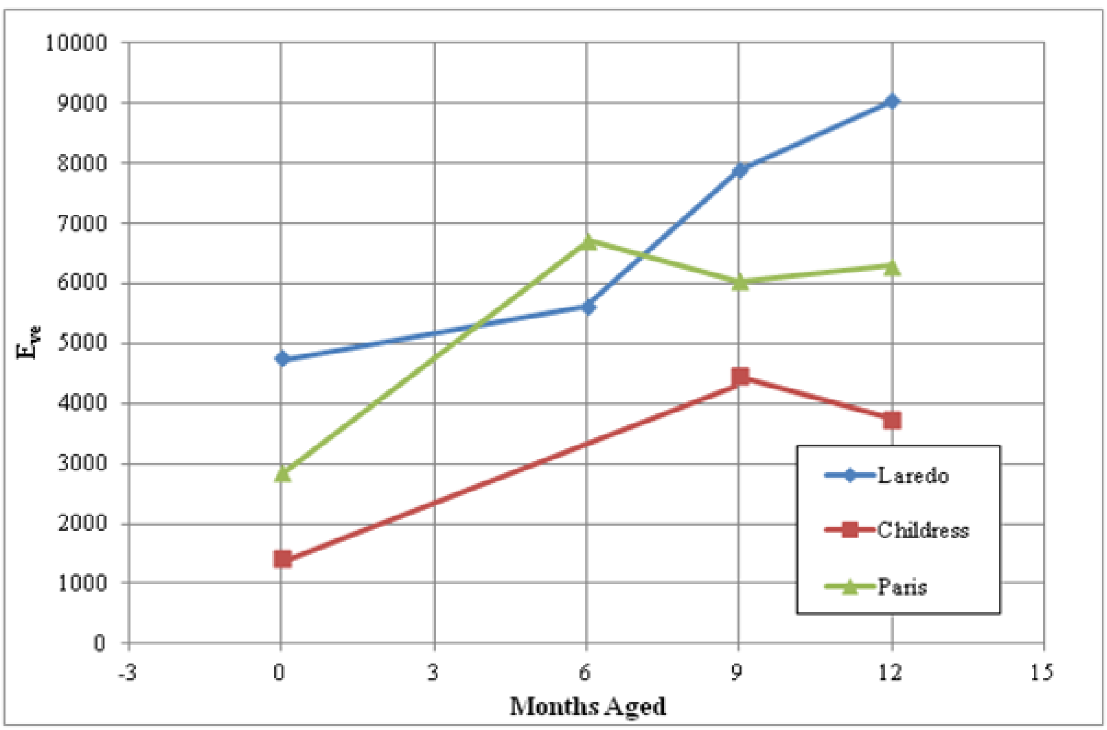


Figure 8: E_{ve} for all three sites at medium AV and optimum binder content at different ages

In Figure 9, similar trends were charted for another type of mixture which had optimum+0.5% binder content and low AV. These mixture conditions are usually considered to be ideal for fatigue resistance of HMA. The trends observed were similar to the ones seen in Figure 8. Stiffness showed a considerable increase with time and Childress had the lowest modulus. The modulus values at each aging level are higher than the corresponding modulus values at optimum conditions. It can be concluded that a combination of optimum -0.5% binder content and low AV is stiffer than a mixture with optimum binder content and medium level AV.

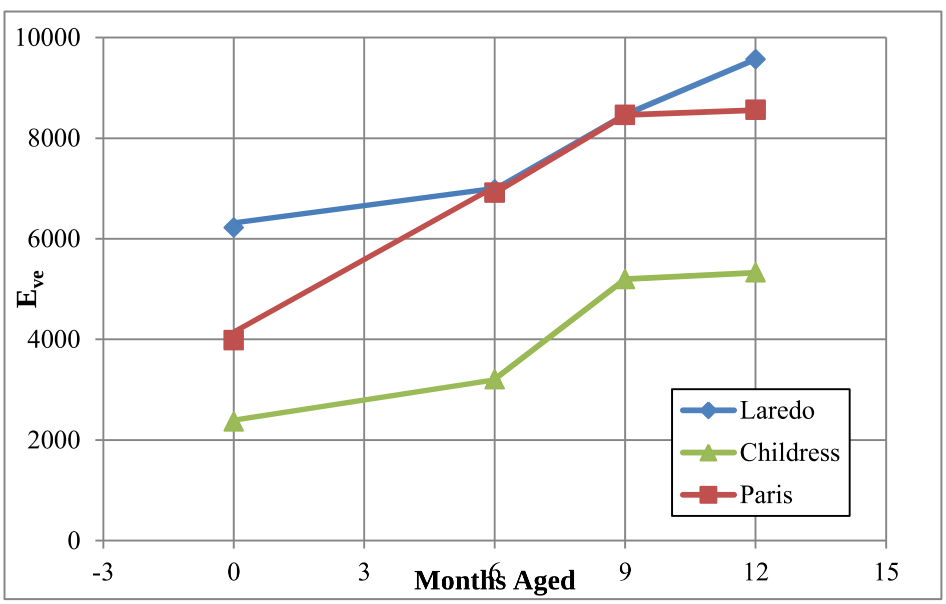


Figure 9: E_{ve} for all three sites at low AV and optimum-0.5% binder content at different ages

An Analysis of Variance (ANOVA) test on the test results of Laredo concluded that there are statistically significant effects of aging level, binder content and AV on E_{ve} while there are no statistically significant interaction effects among them (i.e., the rate of change in E_{ve} over different aging levels are not statistically different over different AV or over different binder contents). A Tukey HSD statistical test confirmed that E_{ve} was statistically different at each aging level.

Figure 10 shows how E_{ve} changes over time with low, medium and high AV contents for the Laredo mixture. As expected, the modulus increased as the sample ages. Low AV mixtures have a higher E_{ve} value compared to the mixtures with medium and high AV. While the medium and high AV samples appeared to have very similar E_{ve} values at 6 months, the Tukey HSD analysis for the effect of AV indicated E_{ve} was significantly different overall among all three AV contents. Also, the rate of change in E_{ve} over time is similar for all three AV contents as expected from the insignificant interaction effect test results between aging levels and AV contents

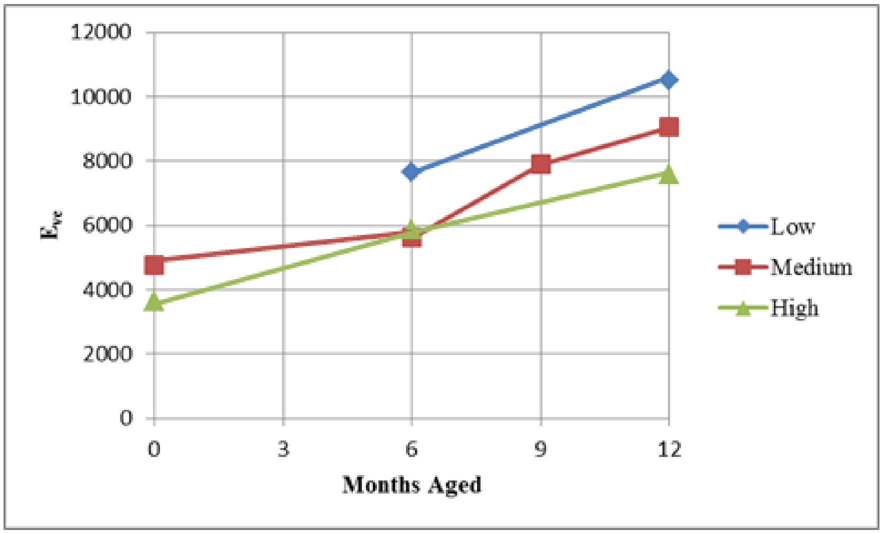


Figure 10: E_{ve} for Laredo at differing AV and optimum binder content

Figure 11 shows the change in the E_{ve} values for the Laredo mixture at three different binder contents: optimum, optimum -0.5% and optimum +0.5%. The rate of change in E_{ve} appears approximately the same for the optimum and optimum -0.5% binder contents, but is slightly slower for the optimum +0.5% binder content. ANOVA test on the interaction effect between binder contents and aging levels indicated that the rate of change in E_{ve} across three binder contents was not statistically significantly different. Tukey HSD analysis on the main effect of binder content indicated that overall there was no considerable difference in E_{ve} based on binder content for optimum and optimum +0.5% while a significant difference did exist between these two and optimum -0.5%.

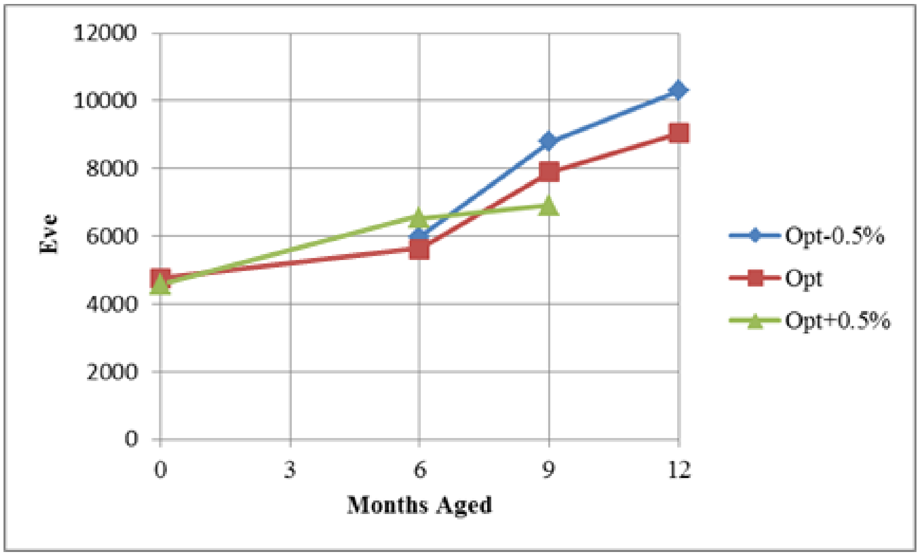


Figure 11: E_{ve} for Laredo at differing binder content and medium AV

As shown in Figures 12-15, similar trends were charted for the other two sites. In general, AV seems to be a more significant factor in comparison to binder content. In the case of Childress, there was an interaction effect between the aging and AV and aging and binder content.

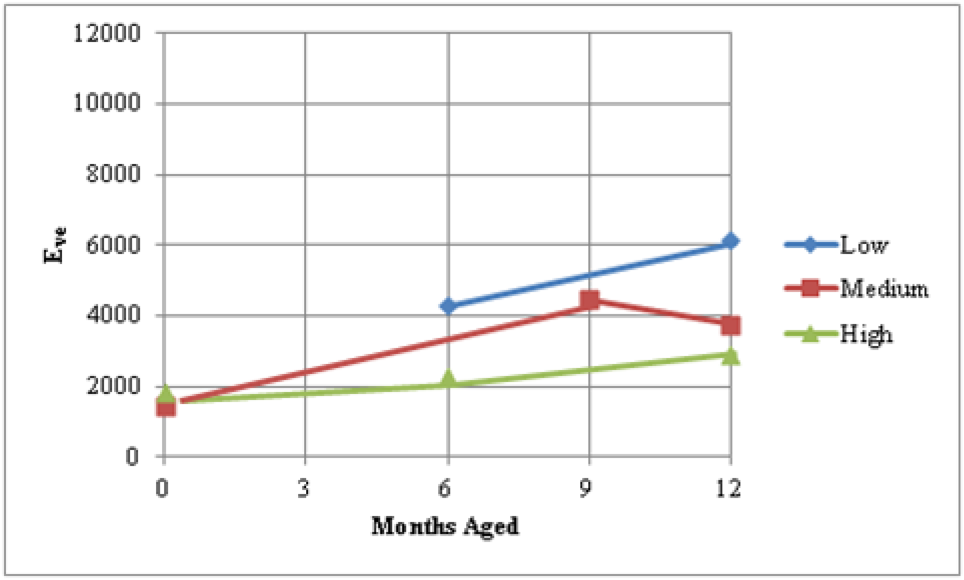


Figure 12: E_{ve} for Childress at differing AV and optimum binder content

From the results of Tukey's HSD for Childress, for all the AV levels, 0 months was observed to be significantly different from 6, 9 and 12 months aging levels. In the case of 6 months and 12 months aging levels, low and high AV were noted to be considerably different from each other. In the case of 0 months and 9 months, the three levels of AV appeared to be the same.

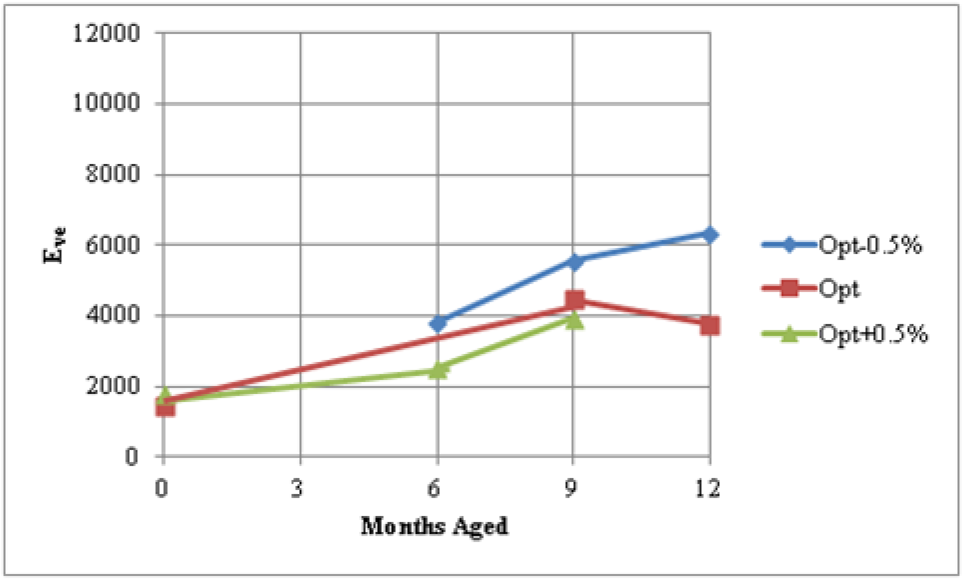


Figure 13: E_{ve} for Childress at differing binder content and medium AV

Studying the interaction effects, it can be concluded that at any particular aging level, optimum -0.5% was observed to different from optimum and optimum+0.5% binder contents.

In the case of Paris, an interaction effect between aging and AV was observed. The three AV levels at unaged conditions are different from the AV levels at 6, 9 and 12 months levels. In case of a particular aging level, all AV levels were observed to be different from each other.

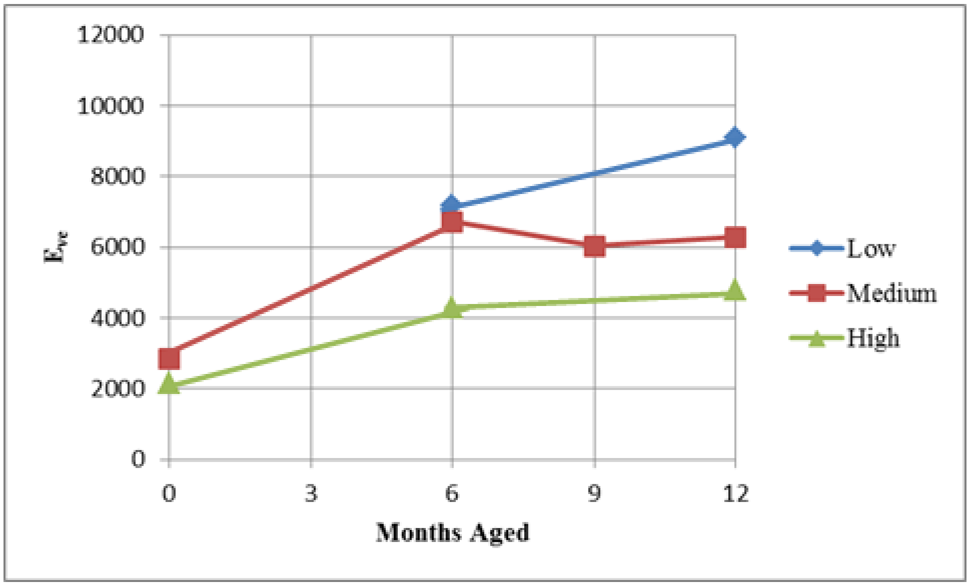


Figure 14: E_{ve} for Paris at differing AV and optimum binder content

Conversely, binder content seemed to show a significant effect on E_{ve} in the case of Paris. Optimum +0.5% has lower stiffness values than optimum and optimum-0.5%. In case of this particular site, it can be concluded that an increase in the binder content causes a decrease in stiffness.

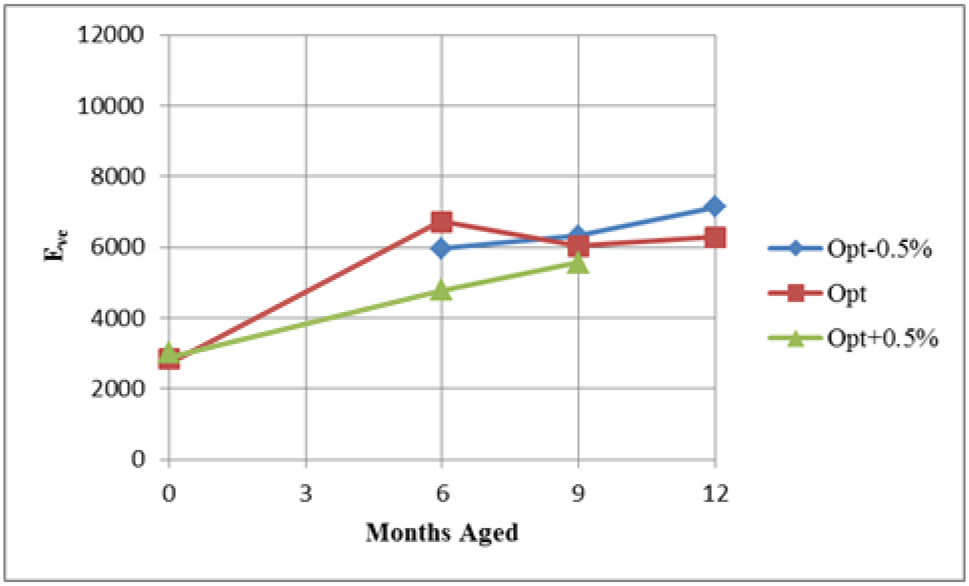


Figure 15: E_{ve} for Paris at differing binder content and medium AV

Another way to analyze the effects of the mix design parameters on the Stiffness would be look at the effects of film thickness in each of these mixtures. The film thickness does a good job of capturing the cumulative effect of the AV level, binder content, type of mixture, etc. As the nature of each of these three mixtures is different in so many respects, the film thickness can help shed some light on their behavior. The film thickness values calculated were 6.0, 10.3 and 7.4 microns for LRD, CHS and PAR respectively. This could help explain the lower modulus in the case of CHS in comparison to the other mixtures.

EFFECT ON NUMBER OF CYCLES TO LOAD FAILURE (N_f)

Figure 16 shows the N_f for the three mixtures at optimum binder content and medium AV. N_f for Childress decreased with age which is consistent with the observation that the mixture stiffens with age and becomes more susceptible to failure. Laredo and Paris show slight increases in N_f with time; however, the overall trends are relatively stable when compared with that for Childress. Based on these results, the Childress mixture is more sensitive to the effects of aging.

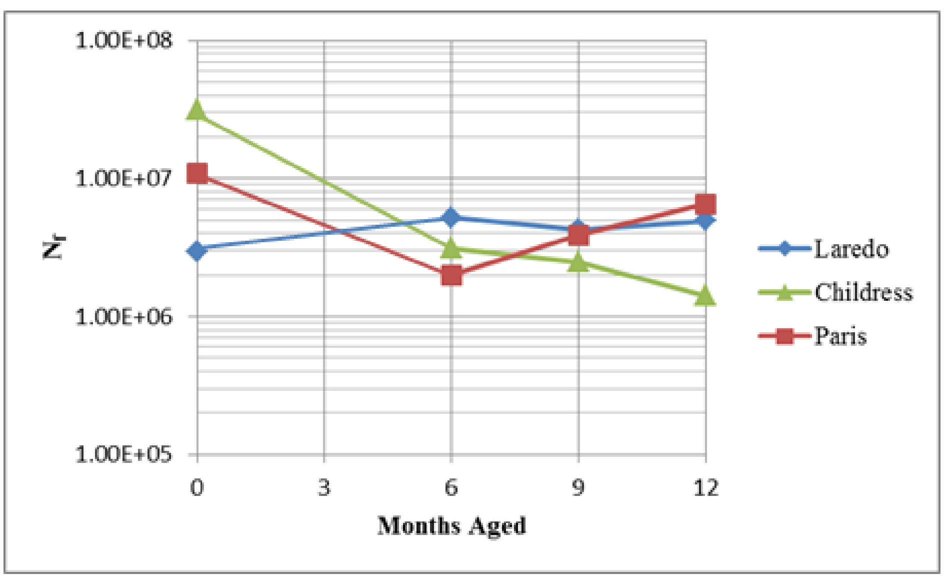


Figure 16: N_f for all three sites at medium AV and optimum binder content

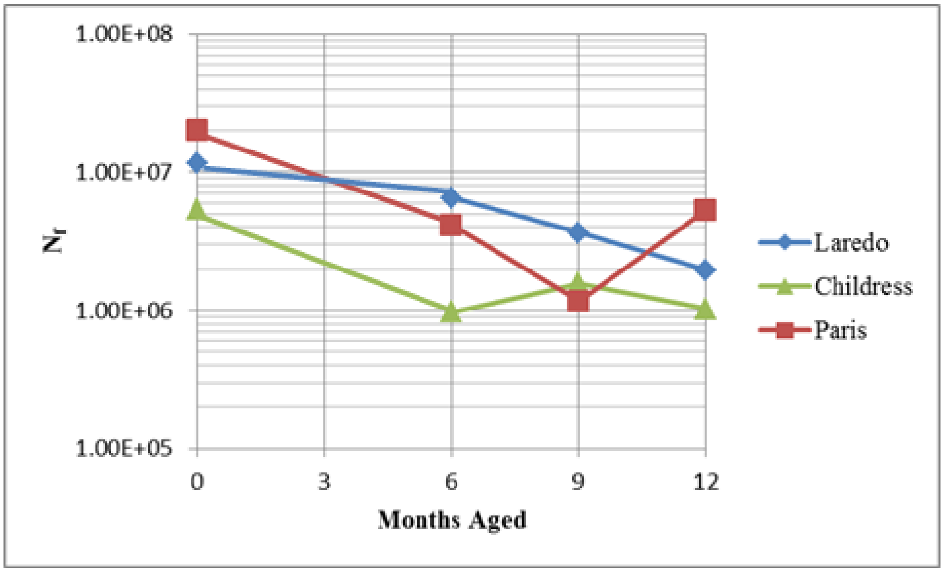


Figure 17: N_f for all three sites at low AV and optimum-0.5% binder content

Figure 17 shows the trends for a different type of mixture which has Optimum +0.5% and low AV. Laredo shows a considerable decline with age which shows that the mixture is getting stiffer and thus losing resistance to damage. In the cases of Childress and Paris, there is a significant decrease from 0 months to 6 months. The number of load cycles to failure (N_f) appears to be characteristic of the mixture type.

The results of ANOVA and Tukey's HSD for Laredo showed that none of the effects in the model were statistically significant. In case of Childress and Paris, aging was found to be the only substantial factor among the three factors. AV and binder content do not seem to have a significant effect on N_f.

EFFECT ON CRACK RATIO (C')

A new parameter called the crack ratio was defined to help understand the resistance to crack growth due to aging in the asphalt mixtures. It is a measure of the crack growth in the sample during the test. It can be defined as:

$C' = (C_{1000} - C_0)/C_0$

C_{1000} = crack size at 1000 cycles

C_0 =crack size at 0 cycles

Figure 18 shows the change in crack ratio with age for the three different mixtures. Laredo shows an increase with age which is as expected as the mixture gets stiffer with age and thus becomes more susceptible to damage. Childress and Paris show an increase from 0 months to 6 months and then start to level off. This could imply that each mixture has a maximum limit after which the damage accumulation does not increase.

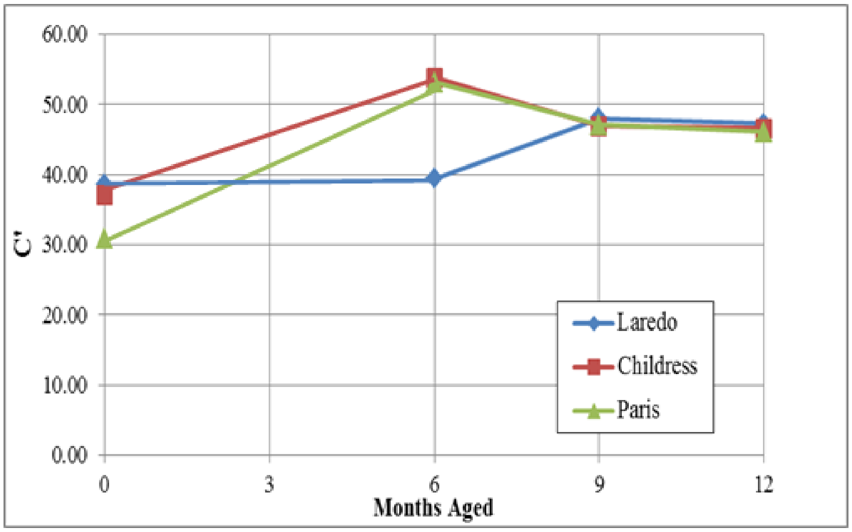


Figure 18: *C'* for all three sites at medium AV and optimum binder content

Results from the statistical analysis suggest that the crack ratio is highly dependent on the type of mixture. In case of Laredo, interaction effects were observed between all three factors. In case of Childress, only aging showed a significant effect on *C'*. On the other hand, both aging and AV were observed to be the important factors in Paris. An increase in AV showed a corresponding increase in *C'*. This would be expected as a higher AV content would make the mixture more prone to crack growth.

EFFECT ON RATE OF DAMAGE ACCUMULATION (b)

The constant *b* is expected to relate inversely to mixture fatigue resistance. Generally, a comparatively small value of *b* indicates a relatively low rate of accumulation of micro-fatigue damage, and consequently high HMA mixture fatigue resistance.

Figure 19 shows there is a general upward trend in *b* in the cases of Laredo and Paris. This suggests that the fatigue resistance of the mixture is going down with age and the mixture is more susceptible to damage. However, in case of Childress, *b* does not seem to show much change with age. This could indicate that the rate of damage accumulation slows down after a certain period depending on the mixture type. Childress being the softest of the three mixture types might have reached the upward limit of damage accumulation before the other two mixtures.

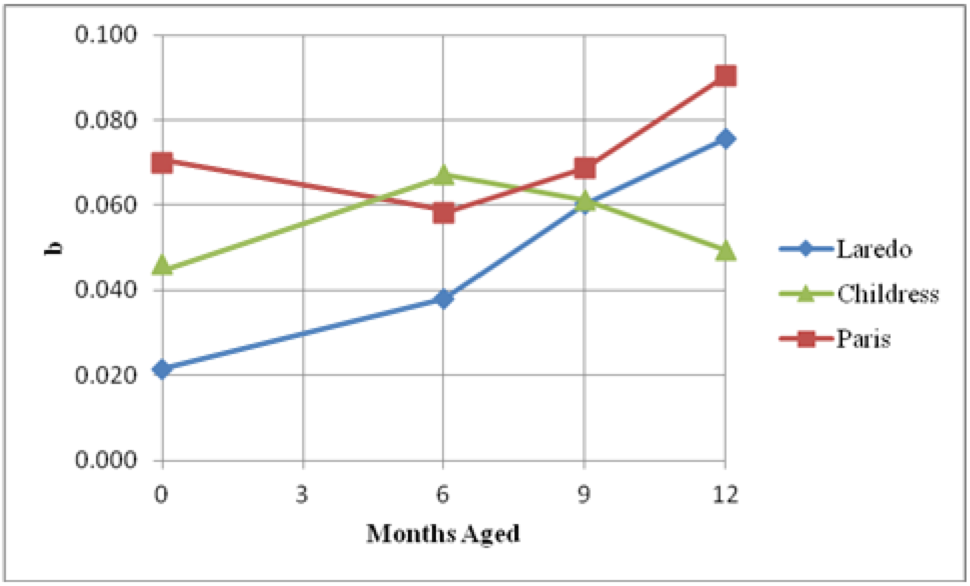


Figure 19: *b* for all three sites at medium AV and optimum binder content

Statistical analysis of the *b* data for all sites shows that there are no significant effects of aging, AV or binder contents on *b* in the cases of Laredo and Childress. On the other hand, aging seems to have an important effect on *b* in the case of Paris.

EFFECT ON PARIS LAW FRACTURE COEFFICIENT (A)

The Paris law of fracture can be defined as

$$\frac{dc}{dN} = A[K]^{n}$$

K = stress intensity factor

dc/dN = Crack growth rate per load cycle

and A and n are the Paris law of fracture coefficients

Generally, A is inversely proportional to the resistance to fatigue damage. As shown in Figure 20, it is expected that A will increase with an increase in binder oxidative aging, leading to a consequent reduction in fatigue resistance (4,13).

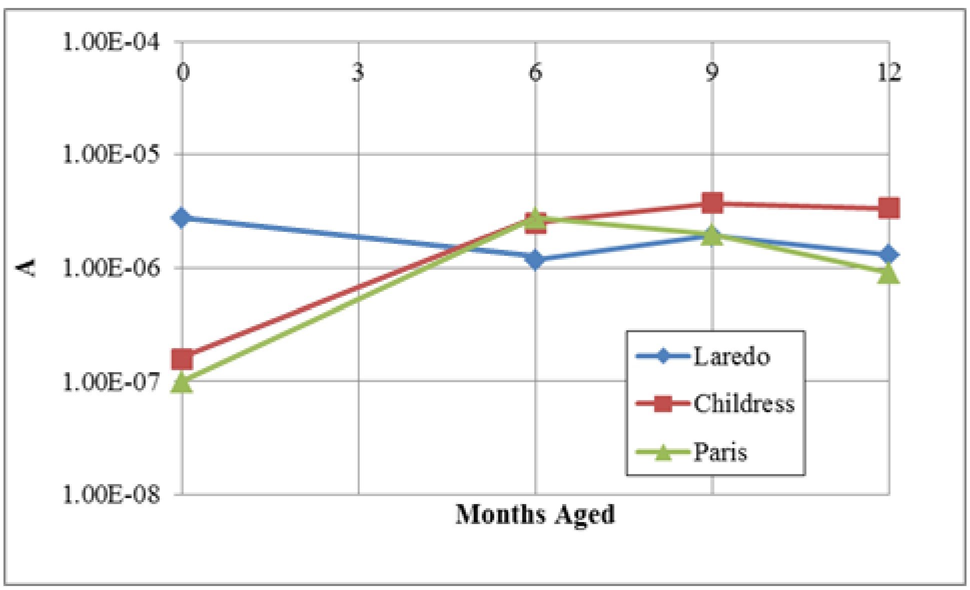


Figure 20: A for all three sites at medium AV and optimum binder content

From the LMLC results, age does not seem effect *A* in the case of Laredo. But, in the case of Childress and Paris, a considerable initial jump can be observed from 0 to 6 months, and then it starts to even out with not much change.

The statistical analysis of these results showed that the influence of mixture parameters varies from mixture to mixture. The logarithm of *A* was analyzed using ANOVA and Tukey's HSD tests. In the case of Laredo, none of the three factors were statistically significant. In case of Childress and Paris, aging was observed to be a significant factor.

All statistical results have been summarized in the Table 5.

Table 5: Statistical analysis of effects of mixture parameters on the fatigue damage characteristics

Parameter	Laredo	Childress	Paris
E_{ve}	All three main effects are statistically significant	Interaction effects between (Aging and Binder Content) and (Aging and AV) are significant	Interaction effects between (Aging and AV) and Binder content are statistically significant

Table 5, Continued.

Parameter	Laredo	Childress	Paris
b	None of the effects in the model are statistically significant	None of the effects in the model are statistically significant	Only aging has a significant effect
A	None of the effects in the model are statistically significant	Interaction effects exist between Aging and AV	Only aging has a significant effect
N_f	None of the effects in the model are statistically significant	Only aging has a significant effect	Only aging has a significant effect
C	All interaction effects between the three factors are significant	Only aging has a significant effect	Effects of Aging and AV are statistically significant

CORRELATIONS WITH FIELD AND BINDER DATA

With testing and analysis results obtained for binders, field samples and LMLC samples; it is possible to make some comparisons between the results. A connection between binder aging and field performance along with a correlation between field and LMLC mixture performance may provide the information required to predict the effects of aging on the performance of HMA in the field.

CORRELATION WITH BINDER DATA

The data obtained from the LMLC samples were compared with the binder data obtained from the chemical studies conducted by others. The measured properties of the binder Carbonyl area (CA) was correlated with the modulus values. Figures 21 and 22 show a good correlation between the binder and the mixture properties showing that the two different sets of data corroborate on the concept of aging. An increase in CA implies that the binder gets stiffer with age which is confirmed with the stiffness of the mixtures.

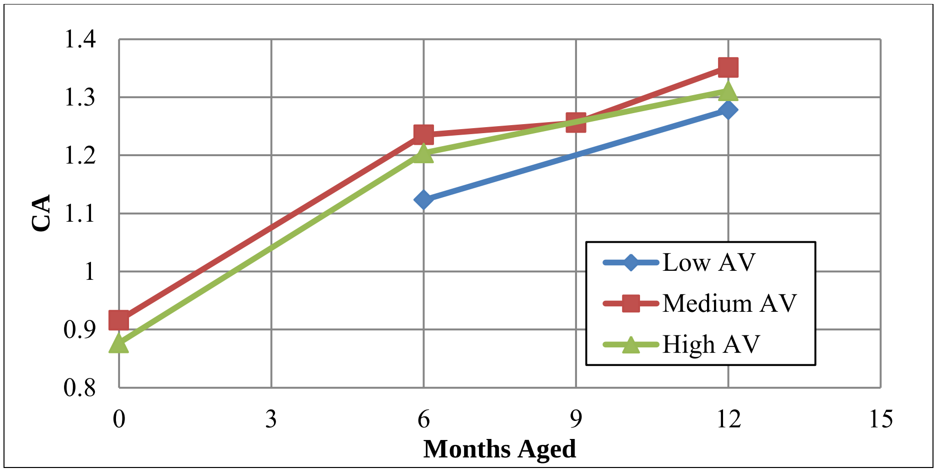


Figure 21: CA for LMLC samples at optimum binder content with differing AV and increasing age for Laredo

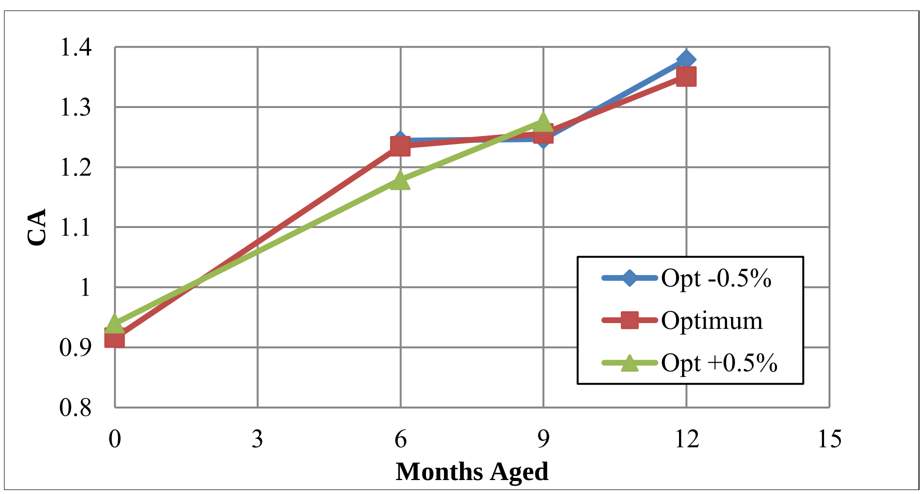


Figure 22: CA for LMLC samples with medium AV and differing binder contents and increasing age for Laredo

Comparing the E_{ve} values of the LRD samples versus the corresponding CA from their respective extracted binders it can be seen that the two properties are related. Figure 23 shows the relationship between E_{ve} and CA for the LMLC samples at low, medium and high AV. All three sets of samples show that a correlation exists between CA and E_{ve} for mixtures, with a strong correlation for the high AV samples.

The same can be said when viewing the LMLC samples at optimum, optimum -0.5% and optimum +0.5% binder contents as seen in Figure 24. Optimum and optimum +0.5% binder contents appear to show an acceptable correlation between CA and E_{ve}, with the higher binder content having a much stronger correlation. Thus, it can be stated that there is a strong relationship between binder oxidation, resulting binder stiffening, and ultimate mixture stiffening with aging.

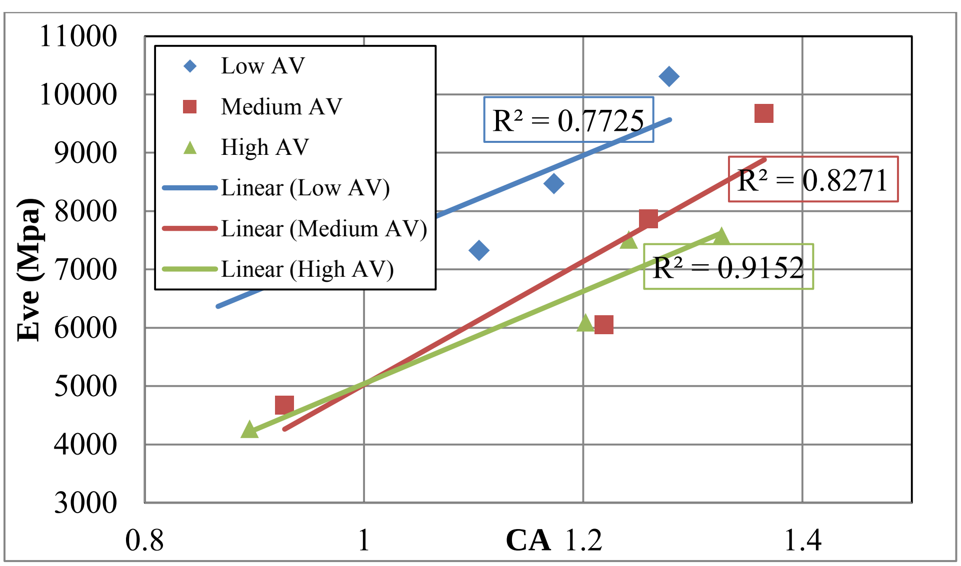


Figure 23: E_{ve} vs. CA for LMLC samples with differing AV and increasing age for Laredo

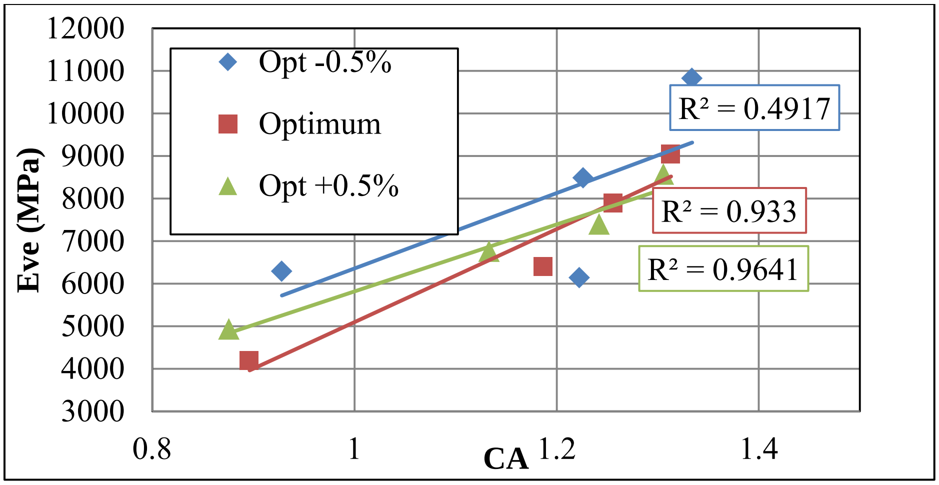


Figure 24: E_{ve} vs. CA for LMLC samples at differing binder content and increasing age for Laredo

Similar charts were plotted in the case of Childress in Figure 25 and Figure 26 and Paris in Figure 27 and Figure 28. They show a general upward trend in the case of of the other two mixtures. The slope is steeper in the case of Paris which agrees with the correpsonding trends of the stiffness modulus in Figures 14 and 15.

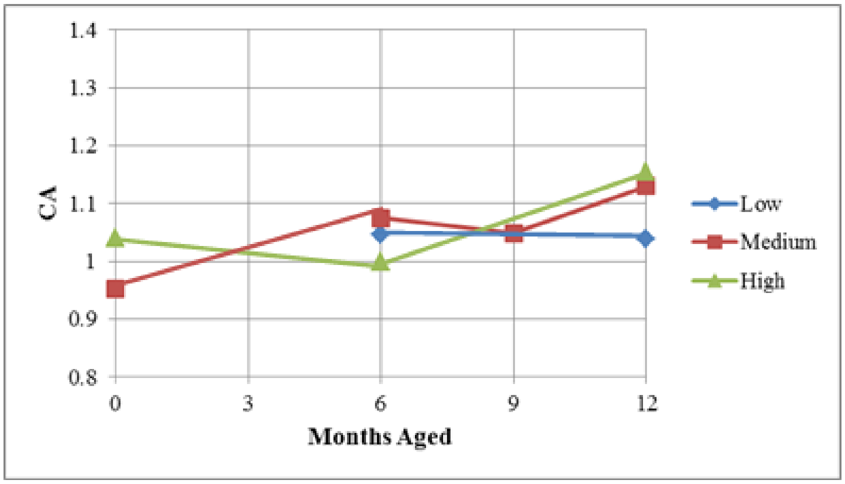


Figure 25: CA for LMLC samples at optimum binder content with differing AV and increasing age for Childress

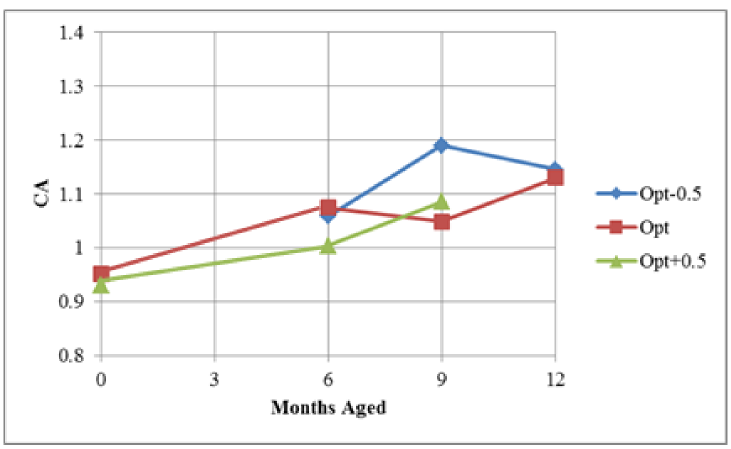


Figure 26: CA for LMLC samples with medium AV and differing binder contents and increasing age for Childress

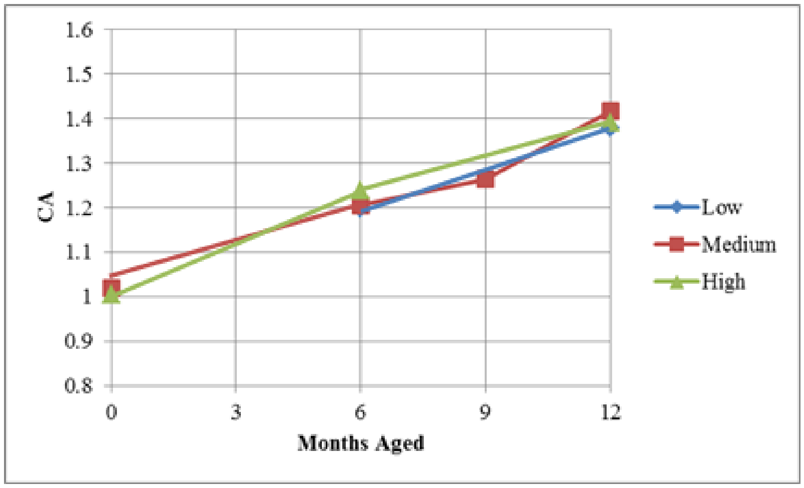


Figure 27: CA for LMLC samples at optimum binder content with differing AV and increasing age for Paris

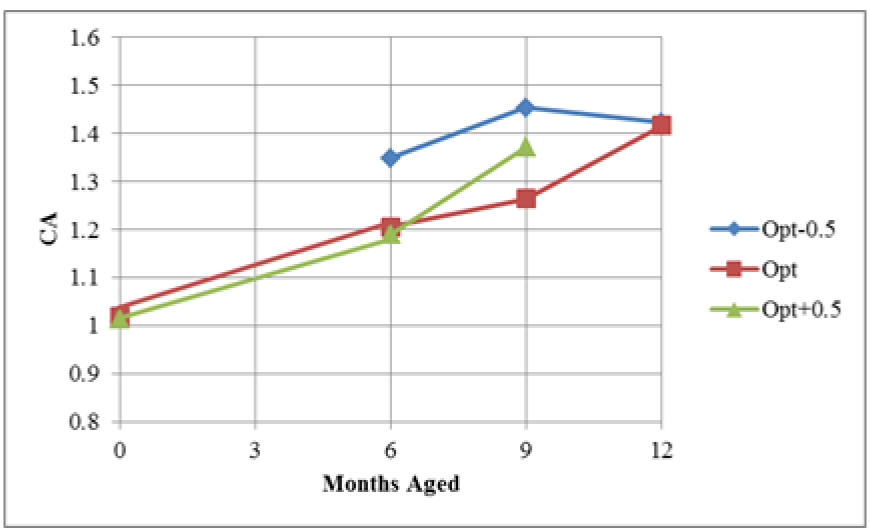


Figure 28: CA for LMLC samples with medium AV and differing binder contents and increasing age for Paris

Similar comparisons have been carried out between the E_{ve} and the DSR function of the extracted binder. These trends have been studied in the case of differing air voids and differing binder contents for all the three different sites. Figure 29 shows the trends between E_{ve} and the DSR at optimum binder content and different AV levels for Laredo.

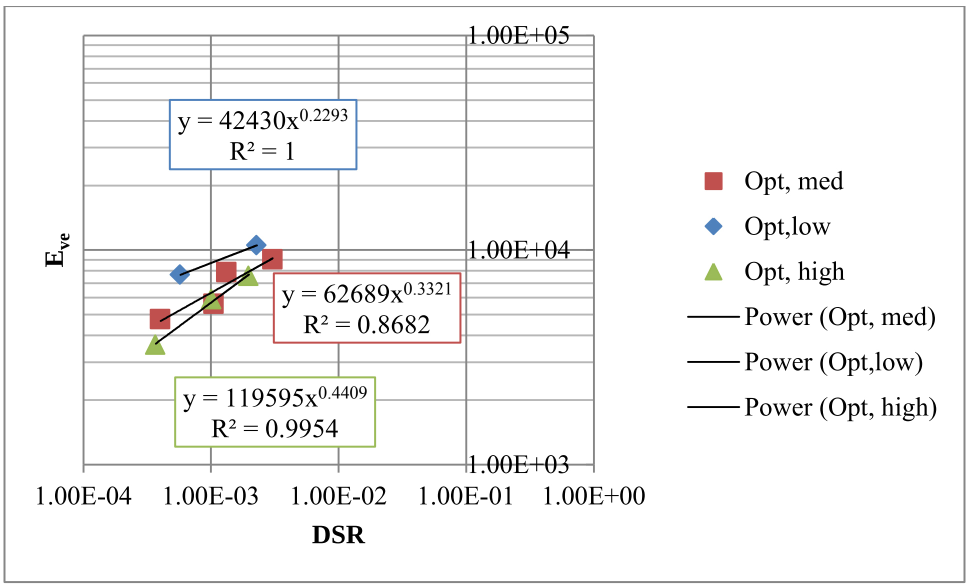


Figure 29: E_{ve} vs. DSR for LMLC samples at differing air voids and increasing age for Laredo

The plot shows fairly good correlations between the E_{ve} and DSR for all the different AV levels. E_{ve} and DSR show a consistent increase with age and the slopes seem to increase with an increase in AV content. This would be expected as higher AV implies more exposure to oxygen which would lead to steeper increase in E_{ve} with respect to

DSR. Figure 30 shows a similar correlation at differing binder contents at medium AV level.

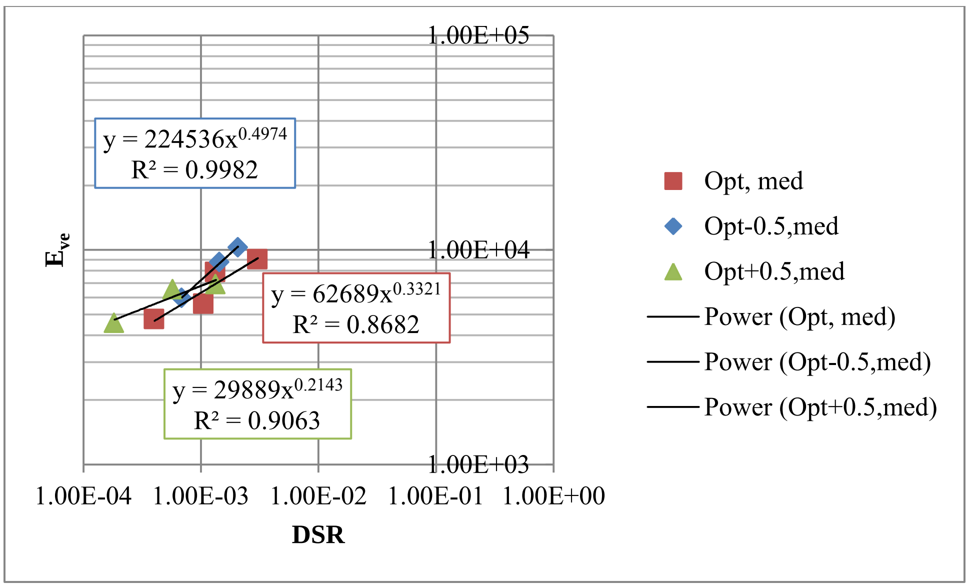


Figure 30: E_{ve} vs. DSR for LMLC samples at differing binder contents and increasing age for Laredo

Figure 30 also shows a good correlation between the two properties which shows that a definite relationship exists between the mixture and binder properties. In case of the differing binder contents, it can be observed that the slope is inversely proportional to the binder content. Opt-0.5% has the highest slope while Opt+0.5% has the lowest slope out of the three binder contents.

Similar trends were plotted in the cases of CHS and PAR in Figures 31, 32, 33 and 34.

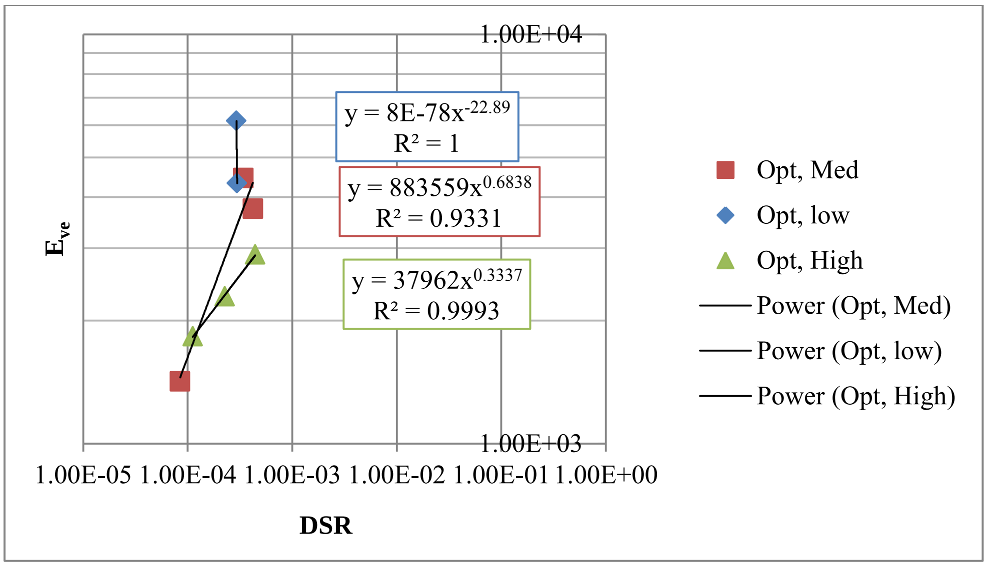


Figure 31: E_{ve} vs. DSR for LMLC samples at differing air voids and increasing age for Childress

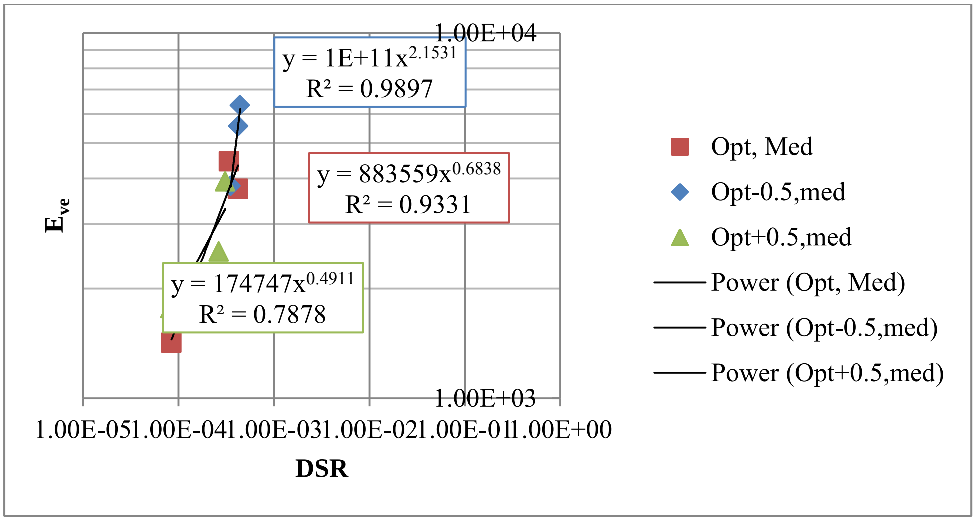


Figure 32: E_{ve} vs. DSR for LMLC samples at differing binder contents and increasing age for Childress

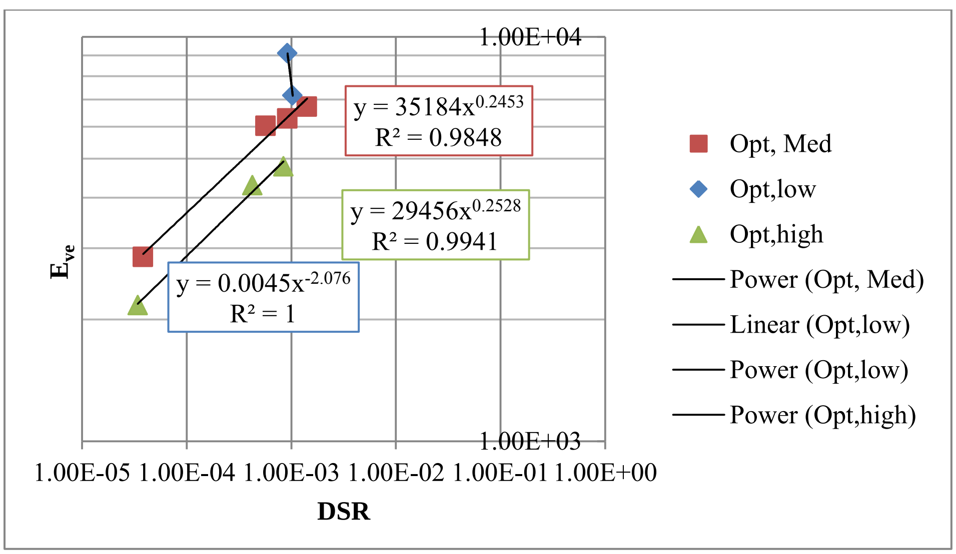


Figure 33: E_{ve} vs. DSR for LMLC samples at differing air voids and increasing age for

Paris

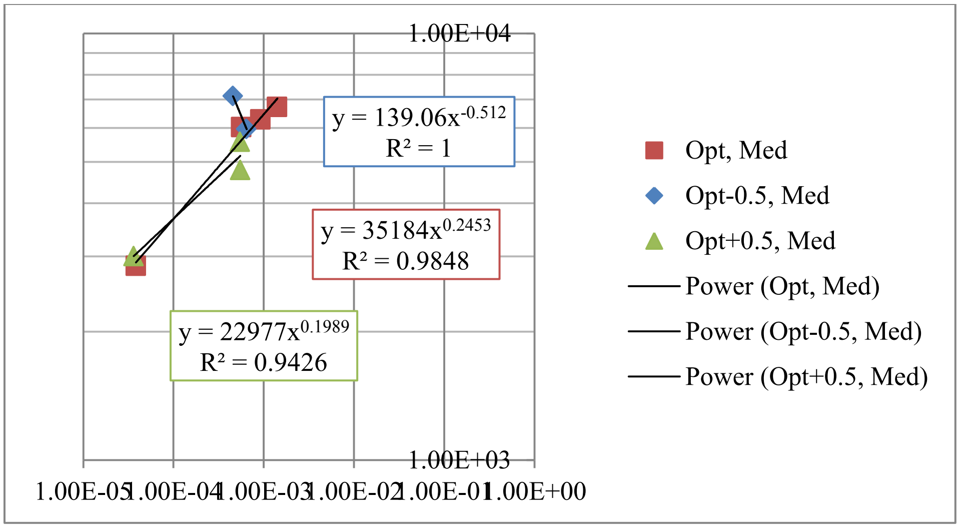


Figure 34: E_{ve} vs. DSR for LMLC samples at differing binder contents and increasing age for Paris

Figures 31, 32, 33 and 34 show a good correlation between the E_{ve} and DSR function. Both the parameters show an increase with age as the mixture stiffens. Figures 32 and Figure 34 agree with the previous observation that the binder content is inversely proportional to the slope of the increase in E_{ve} with respect to DSR. This holds true in all the three cases. Figure 33 shows that the AV level is inversely proportional to the slope which also agrees with the results in case of Laredo in Figure 29.

CORRELATION WITH FIELD DATA

The laboratory samples were only exposed to accelerated laboratory aging and experienced no traffic loading prior to testing. In order to make an equivalent comparison to performance in the field, it is important to compare the LMLC sample results with field results from samples which had minimal exposure to traffic loading. To accomplish this, a comparison was made between the LMLC samples and the field samples taken from the three sites and the results gathered by others.

By plotting the two lines representing the linear fit of E_{ve} for the LMLC and field samples on the same graph, the relationship between field and LMLC samples can be easily seen. Figure 29 shows the combined results of the LMLC and field sample E_{ve} values. The top axis represents the artificial aging period for the LMLC samples while the bottom axis is the actual age of the HMA layer in the field. By adjusting the axes to fit the field E_{ve} to the LMLC E_{ve}, it was determined that one month of aging in the laboratory was equivalent to 10.5 months of aging in the field for both US 277 and US 83. SH 24 data could not be aligned without a vertical shift in the LMLC results; however, the trends between laboratory and field with the 1:10.5 comparison are similar for all three sites. This also agrees with previous studies that have showed that one month of aging of binder in the laboratory at 60 °C compares to 13 to 19 months in the pavement (5). It has to be recognized that these studies were conducted on binders while the current results deal with mixture data which could explain the slight difference in the factors.

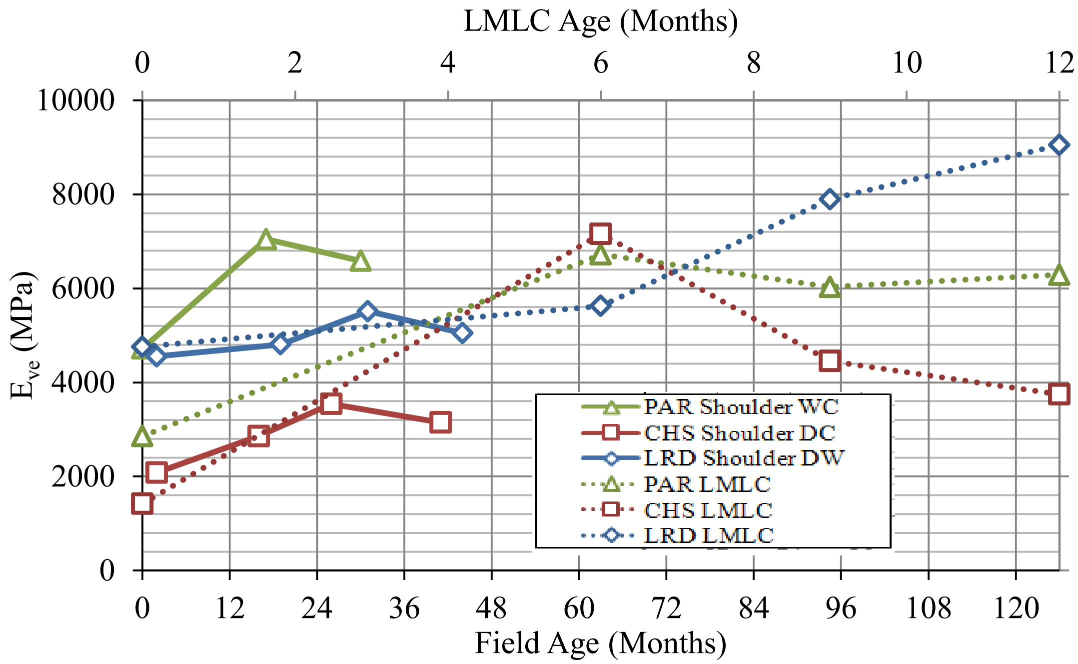


Figure 35: LMLC and field sample combined E_{ve} results.

The combined graphical results for N_f are shown in Figure 30. As expected, the N_f values either decrease or remain relatively constant for both the LMLC and field samples as they age. These encouraging results indicate that a relationship exists. The significant difference between the LMLC and field results could also be due to the fact that the shift factors accounting for anisotropy and healing have not been utilized in the CMSE* method adopted in this study. However, since there are many factors which play a role in the calculation of N_f, a simple relationship like that shown with the E_{ve} values is insufficient. In order to more closely relate the LMLC sample N_f results to the field N_f results, a more complex model needs to be developed.

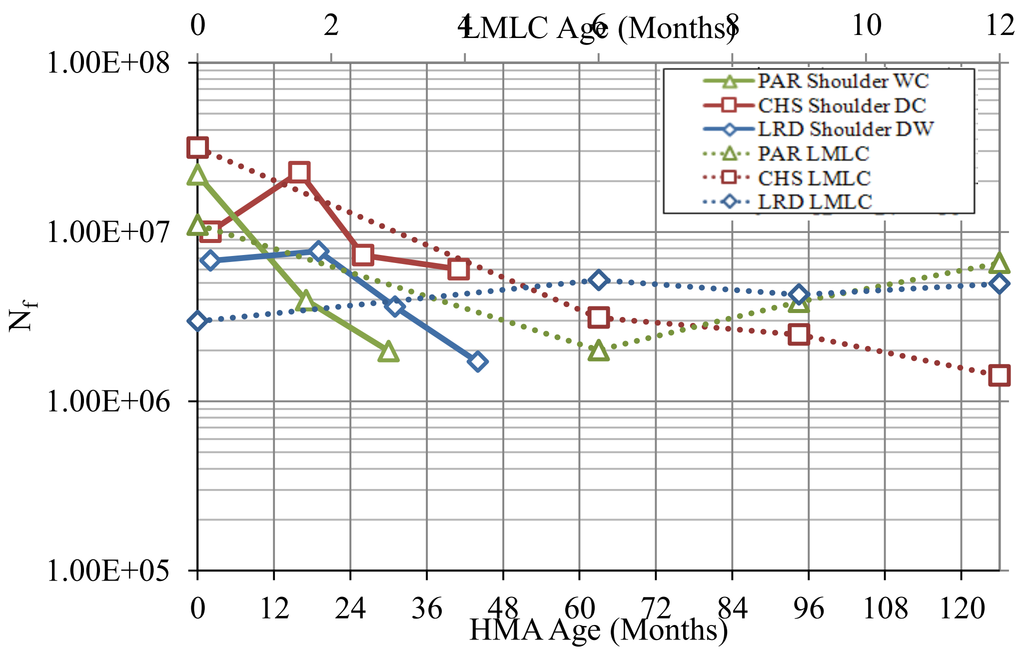


Figure 36**:** LMLC and field sample combined N_f results

CHAPTER V

CONCLUSIONS AND RESEARCH

Characterizing the role of aging in the development of fatigue failure in HMA mixtures is not a simple task. There are many factors which play a role, not only in fatigue cracking as a whole, but also in the aging process. In order to effectively characterize and predict HMA aging in the field, aging in LMLC mixtures must be understood and correlated with actual field performance.

This study shows that HMA aging through binder oxidation not only occurs, but plays a significant role in the development of fatigue failure. A comparison can be made between artificially laboratory aged LMLC samples and naturally aged field cores taken from the shoulder, where minimal trafficking occurred. For the three sites in Texas included in this study, when comparing E_{ve}, one month of artificial aging in the laboratory was equivalent to 10.5 months in the field.

Future studies should include the further development of a more mechanistic model to predict N_f in the field from mixture data collected from unaged LMLC samples available during mixture design and collected unaged binder data, in combination with accelerated laboratory aged binder data or aged binder data calculated using existing models. This can be accomplished by developing the relationship between artificially laboratory aged LMLC N_f values and N_f values obtained from naturally aged field samples. By developing this relationship with field cores taken from the shoulder, the impact of aging without the confounding effects of traffic can be better understood and predicted. With these components, a pavement prediction model that accounts for aging and its impact on N_f in the field can be fully developed.

The laboratory test results from LMLC and field samples and corresponding extracted binders lead to the following important conclusions regarding HMA aging.

a. Aging does play a role in the fatigue failure of HMA as evidenced in the LMLC samples. The stiffening of a mixture also coordinates well with an increase in oxidation, represented by CA and DSR development in corresponding extracted binders.
b. While both AV and binder content play a role in mixture aging, AV plays a much more significant role in influencing the damage properties.
c. Film thickness could be a more suitable factor to understand the cumulative effects of air voids, binder content, and type of mixture.
d. The loss of the fatigue resistance with age is tied to the mixture type.
e. The effects of the mixture parameters on the fatigue damage characteristics vary from mixture to mixture.
f. The CMSE* method gives good results with low variability and shows promise in capturing the effects of aging on HMA mixture fatigue resistance.

g. It is possible to develop a relationship between binder aging and mixture aging. A relationship can also be drawn between artificially aged LMLC samples and realistically aged field samples.

These generalized conclusions are an important first step in moving toward mechanistic models which incorporate and quantify aging. A relationship between binders and LMLC samples, and between LMLC samples and field samples, lends itself to the potential development of prediction models which incorporate aging. The next step in this development requires a deeper investigation into other field sites with different mixture and environmental conditions. While the findings from this study are a good starting point, a quality fatigue failure prediction model must be applicable to a wide range of HMA mixtures in all types of climates and conditions.

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APPENDIX

Table A-1: TxDOT Type C Master Gradation Bands (% Passing by Weight or Volume)

Sieve Size		Type C
#	mm	Fine Surface
3/4"	19.0	100.0
1/2"	12.5	95 - 100
3/8"	9.5	70 - 85
No. 4	4.75	43-63
No. 8	2.36	32 - 44
No. 30	0.600	14 - 28
No.50	0.300	7 - 21
No. 200	0.075	2 – 7

Table A-2: Mix Design of Laredo

	BIN FRACTIONS								
	Bin No.1		Bin No.2		Bin No.3		Bin No.4		
Aggregate Source:	SO. TX. AGG.		SO. TX. AGG		SO. TX. AGG		VULCAN		
Aggregate Pit:	SABINAL		SABINAL		SABINAL		KNIPPA		
Description:	Gr. 3		D / F Blend		Mfg. Sand		Mfg. Sand (TR)		
Individual Bin (%):	21.0	Percent	31.0	Percent	29.0	Percent	19.0	Percent	100.0%
Sieve Size:	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum. % Passing
in mm									
1" 25.400	100.0	21.0	100.0	31.0	100.0	29.0	100.0	19.0	100.0
3/4" 19.000	100.0	21.0	100.0	31.0	100.0	29.0	100.0	19.0	100.0
3/8" 9.500	6.2	1.3	96.6	29.9	100.0	29.0	100.0	19.0	79.2
No. 4 4.750	1.1	0.2	37.4	11.6	99.9	29.0	99.7	18.9	59.7
No. 8 2.360	0.8	0.2	5.1	1.6	83.6	24.2	85.0	16.2	42.1
No. 30 0.600	0.6	0.1	2.0	0.6	46.1	13.4	24.4	4.6	18.8
No. 50 0.300	0.4	0.1	1.6	0.5	33.9	9.8	11.3	2.1	12.6
No. 200 0.075	0.2	0.0	1.0	0.3	19.1	5.5	1.3	0.2	6.1

Table A-3: Laredo Mix Adjusted Aggregate Gradation based on Wet-Sieve Analysis

Sieve Size		Cumulative % Passing	Specification Limits		Cumulative % Retained	Individual % Retained
			Low	High		
#	mm					
3/4"	19.0	100	100	100	0	0
3/8"	9.5	80.8	85	100	19.25	19.25
No. 4	4.75	61.1	50	70	38.95	19.7
No. 8	2.36	43.9	35	46	56.15	17.2
No. 30	0.600	19.2	15	29	80.85	24.7
No.50	0.300	12.8	7	20	87.25	6.4
No. 200	0.075	6.7	2	7	93.3	6.05

Table A-4: TxDOT Type D Master Gradation Bands (% Passing by Weight or Volume)

Sieve Size		Type D
#	mm	Fine Surface
3/4"	19.0	100.0
1/2"	12.5	98 - 100
3/8"	9.5	85 - 100
No. 4	4.75	50 - 70
No. 8	2.36	35 - 46
No. 30	0.600	15 - 29
No.50	0.300	7 - 20
No. 200	0.075	2 – 7

Table A-5: Mix Design of Childress

		Bin 1		Bin 2		Bin 3				
Aggregate Source:		SNYDER, OK		SNYDER, OK		SNYDER, OK				
Aggregate Pit:		MARTIN MARIETTA		MARTIN MARIETTA		MARTIN MARIETTA				
Description:		Course Granite Aggregate		#4 Crushed Screenings		Crushed Screenings		Lime		Comb Total
Individual Bin (%):		40	%	25	%	33	%	2	%	100
Sieve Size		Cum. % Pass	Wt. Cum. % Pass	Cum. % Pass	Wt. Cum . % Pass	Cum. % Pass	Wt. Cum. % Pass	Cum. % Pass	Wt. Cum. % Pass	Cum. % Pass
#	mm									
3/4"	19.0	100.0	40.0	100.0	25.0	100.0	33.0	100.0	2.0	100.0
1/2"	12.5	97.5	39.0	100.0	25.0	100.0	33.0	100.0	2.0	99.0
3/8"	9.5	71.5	28.6	100.0	25.0	100.0	33.0	100.0	2.0	88.6
# 4	4.75	12.9	5.2	96.8	24.2	95.6	31.5	100.0	2.0	62.9
# 8	2.36	4.6	1.8	73.1	18.3	62.6	20.7	100.0	2.0	42.8
# 30	0.600	2.0	0.8	35.5	8.9	20.0	6.6	100.0	2.0	18.3
# 50	0.300	1.4	0.6	23.0	5.8	9.5	3.1	100.0	2.0	11.4
# 200	0.075	0.7	0.3	9.9	2.5	2.2	0.7	100.0	2.0	5.5

Table A-6: Childress Mix Adjusted Aggregate Gradation based on Wet-Sieve Analysis

Sieve Size		Cumulative % Passing	Specification Limits		Cumulative % Retained	Individual % Retained
			Low	High		
#	mm					
3/4"	19.0	100.0	100	100	0.0	0.0
1/2"	12.5	99.0	98	100	1.0	1.0
3/8"	9.5	88.6	85	100	11.4	10.4
No. 4	4.75	62.9	50	70	37.1	25.7
No. 8	2.36	42.9	35	46	57.1	20.1
No. 30	0.600	18.4	15	29	81.7	24.5
No.50	0.300	11.1	7	20	89.0	7.3
No. 200	0.075	5.2	2	7	94.9	5.9

Table A-7: Mix Design of Paris

		BIN FRACTIONS						
		Bin No.1		**Bin No.2**		**Bin No.3**		
Aggregate Source:		MARTIN MARIETTA		MARTIN MARIETTA		DRAKE		
Aggregate Pit:		SAWYER, OK		SAWYER, OK				
Description:		D rock		Screenings		River sand		
Individual Bin (%):		60.0	Percent	30.0	Percent	10.0	Percent	100.0%
Sieve Size		Cum.% Passing	*Wtd* Cum. %	Cum.% Passing	*Wtd* Cum. %	Cum.% Passing	*Wtd* Cum. %	Cum. % Passing
in	mm							
3/4"	19.000	100.0	60.0	100.0	30.0	100.0	10.0	100.0
1/2"	12.500	100.0	60.0	100.0	30.0	100.0	10.0	100.0
3/8"	9.500	95.3	57.2	100.0	30.0	99.3	9.9	97.1
No. 4	4.750	34.5	20.7	98.9	29.7	99.0	9.9	60.3
No. 8	2.360	12.0	7.2	77.6	23.3	98.3	9.8	40.3
No. 30	0.600	8.0	4.8	42.7	12.8	92.4	9.2	26.9
No. 50	0.300	7.0	4.2	35.7	10.7	48.3	4.8	19.7
No. 200	0.075	1.7	1.0	12.5	3.8	1.4	0.1	4.9

Table A-8: PAR Mix Adjusted Aggregate Gradation based on Wet-Sieve Analysis

Sieve Size		Cumulative % Passing	Specification Limits		Cumulative % Retained	Individual % Retained
			Low	High		
#	mm					
3/4"	19.0	100	100	100	0	0
1/2"	12.5	100	98	100	1	1
3/8"	9.5	97.2	85	100	11.4	10.4
No. 4	4.75	60.7	50	70	37.092	25.692
No. 8	2.36	40.7	35	46	57.227	20.135
No. 30	0.600	27.9	15	29	81.725	24.498
No.50	0.300	21.9	7	20	88.555	6.83
No. 200	0.075	8.6	2	7	94.519	5.964

Table A-9: Summary of input and output variables in the CMSE* analysis. Adapted from Walubita et al. (13)

Source	Parameter
Laboratory test data (HMAC mixture testing of cylindrical specimens)	- Tensile stress & strain - Relaxation modulus (tension & compression) - Uniaxial repeated direct-tension test data (strain, stress, time, & *N*) - Anisotropic data (vertical & lateral modulus) - Dynamic contact angle for asphalt SE - Vapor pressure and adsorbed gas mass for aggregate SE
Analysis of laboratory test data	- Tensile strength - Relaxation modulus master-curves (tension & compression) - Non-linearity correction factor - DPSE & slope of DPSE vs. Log *N* plot - SE for asphalt & aggregates - Healing indices - Healing calibration constants - Creep compliance - Shear modulus - Load pulse shape factor
Field conditions (design data)	- Pavement structure (layer thickness) - Pavement materials (elastic modulus & Poisson's ratio) - Traffic (ESALs, axle load, & tire pressure) - Environment (temperature & moisture conditions.) - Field calibration coefficients - Temperature correction factor

Table A-9, Continued.

Source	Parameter
Computer stress-strain analysis	Design shear strain (γ) @ edge of a loaded tire
Other input parameters	- Reliability level (i.e., 95%) - Crack density - Microcrack length - HMAC brittle-ductile failure characterization - Stress intensity factors - Regression constants - Shear coefficient
Output	- Paris' law coefficients of fracture (A, n) - Shift factor due to anisotropy (SF_a) - Shift factor due to healing (SF_h) - Fatigue load cycles to crack initiation (N_i) - Fatigue load cycles to crack propagation (N_p) - HMAC mixture fatigue resistance (N_f)